Life Cycle Assessment of

Solar-Thermal Heat Generation

Morteza Ardebili

SID: 3302170001

SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy systems

Aug-Nov 2018

HAMBURG - THESSALONIKI

Life Cycle Assessment of Solar-Thermal Heat Generation

Morteza Ardebili

SID: 3302170001

Supervisor:	Prof. Martin Kaltschmitt
Supervising Committee Members:	Dr. Georgios Martinopoulos
	Dr. Anne Rödl

SCHOOL OF SCIENCE & TECHNOLOGY

A thesis submitted for the degree of

Master of Science (MSc) in Energy Systems

Aug-Nov 2018

HAMBURG - THESSALONIKI

Abstract

Solar thermal energy systems can provide hot water for sanitary use, as well as heating. In this research, to compute the environmental effect of using solar thermal energy, we calculate the energy demand of a typical European single-family house, as well as an apartment block in 10 different cities in different climatic conditions. Then with using the F-chart method, the energy production of this system throughout the year will be calculated. Life cycle assessment of the solar thermal system provides us the amount of emission produced per supplied energy by the system. Calculation shows that the emission per kWh of thermal energy highly depends on the longitude of the installation point and demand.

Morteza Ardebili

27/10/2018

Contents

List of Figures

List of tables

List of Abbreviations

EU = European Union

LCA= Life Cycle Analysis

LCI= Life Cycle Inventory

LCIA = Life Cycle Impact Analysis

FPC = Flat Plate Collector

ETC = Evacuated Tube Collector

DHW = Domestic Hot Water

HTF = Heat Transfer Fluid

A_c=Collector area (m^2)

F_R'=collector heat-exchanger efficiency factor

U_L= collector overall loss coefficient (W/m^2-C)

Δt = total number of seconds in the month

T_a= monthly average ambient temperature (C)

T_{ref}= an empirically derived reference temperature (100 C)

H_T= monthly average daily radiation incident on the collector surface per unit area (J/m^2)

L= monthly total heating load for space heating and hot water (J)

N= days in month

$\overline{\tau\alpha}$= monthly average transmittance-absorptance product

F_RU_L = solar collector thermal performance curve slope

$F_R(\tau\alpha)$ = solar collector thermal performance curve intercept

H_T =monthly average daily radiation incident on collector surface per unit area for tilted collector

H = global monthly average daily radiation incident on the horizontal collector

H_D = monthly average daily diffused radiation incident on the horizontal collector surface, β = tilted angle of the surface

ρ = ground reflectance

R_b = extraterrestrial radiation on the tilted surface to that on a horizontal surface for each month

ω = solar hour angle

$\acute{\omega}$ = sunset hour angle for the tilted surface,

φ = latitude of the location,

δ = solar declination

1 Introduction

1.1 Introduction to energy statistics

Based on the very recently published reports of the European Commission (March 2018) 25.4% of the energy of Europe is consumed in the residential sector or households [1]. Energy in houses is consumed mostly in space and water heating, space cooling, cooking, lighting, and electrical appliances.

Most of EU household energy is covered by natural gas (37.1%), and grid electricity (24.5%) and renewables (16%) and the rest is fulfilled by driven heat (central heating system driven by power plants, e.g., in Denmark), petroleum, and coal. (Eurostat, 2018)

64.7% of the total energy in the residential sector used for space heating and 14.5% for hot water production. So, overall around 82% of energy in houses in consumed for space heating and domestic hot water production (Figure 1 & Figure 2).

94.1% of the oil products consumed in dwellings are exclusively used for space heating and water heating. Also, 37.3% of electricity in the residential sector is used for the same application.

Natural gas plays an essential role in term of space heating and hot water production as well, 43.4% and 47.9% of the total energy is consumed by these end users. 22.2% energy needed for space heating and 9.6% of the energy demand for hot water production is covered by renewables like solar energy, geothermal energy, and biomass.

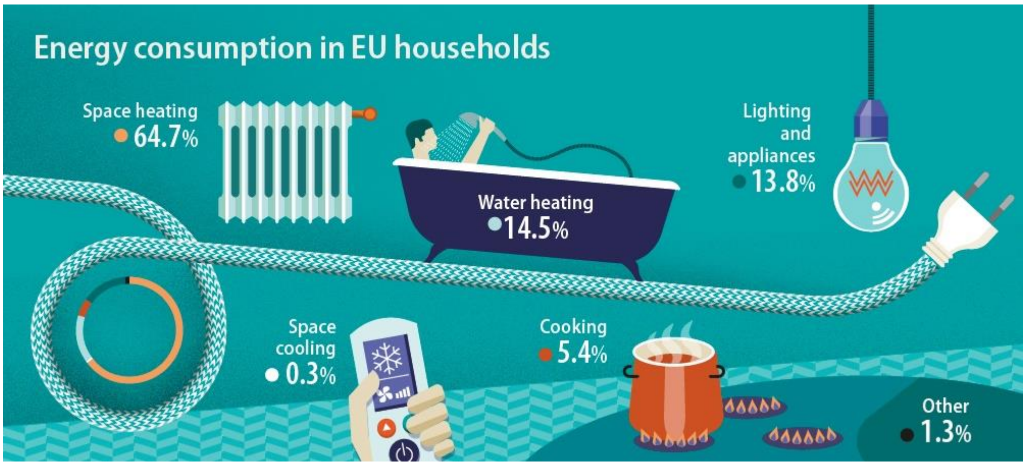

Figure 1 the distribution of energy consumption in Europe houses [1]

Between 28 EU members, eleven of them use mainly renewable energy for space heating of their homes, Portugal with 72% and Croatia with 65% followed by Slovenia with 59% having the largest share of their energy consumption for space heating covered by renewables. However, the countries which using mostly natural gas for space heating are among the largest energy consumers of EU (Netherland, UK, Italy) and three member states (Malta, Greece, and Ireland) are mostly relying on petroleum products.

According to statistics, a quarter of the total energy consumed in Europe, in all possible forms of energy carriers, is used in houses. On average 82% of this energy is used for heating and hot water production for sanitary purposes in all 28 EU countries. It means that 14,306,596 Terajoules out of 68,689,249 Terajoules that have been consumed in the EU in 2016 are just consumed to produce comfortable pleasure temperature in houses. This consumption equals 1.64 million tons of oil equivalent.

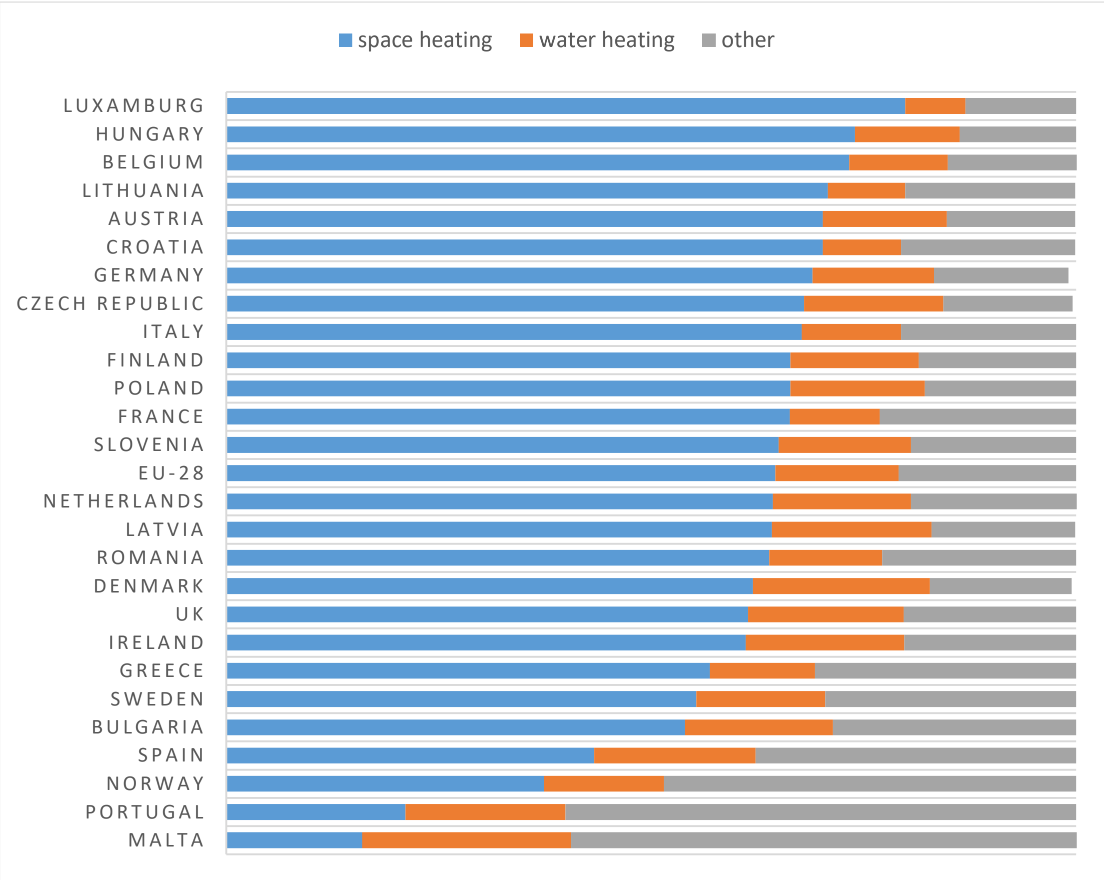

Figure 2 Share of space heating in total residential consumption [2]

1.2 Background

Wind Energy, Solar Energy, Bioenergy, Hydro Energy, and Geothermal, are the primary forms of renewable energy. Solar energy can produce electricity, with photovoltaic panels, or producing heat in a collision with any non-transparent surface.

Photovoltaic panels are well known as an environmentally friendly electricity production method.

On the other hand, using solar thermal systems, for domestic hot water production, is prevalent in the Mediterranean region. Acceptable performance and reduction of energy cost are the principal encouragements for extension of using such systems in prone regions.

Solar Combi system, is a solar heat production system, which is used to produce domestic hot water and space heating, at the same time, with converting solar irradiation to heat. It principally consists of the same elements as a solar water heater, to a greater extent.

This study aims to calculate the environmental effect of using such a system in the residential sector in Europe.

1.3 Aim and Scope

Solar thermal Combi system is converting solar radiation to heat which is transferred to the internal space of the house, to preparing the comfort living temperature inside the dwelling plus the domestic hot water for sanitary uses.

The domestic hot water demand of a house mainly depends on the number of residents, but the space heating demand is a function of some factors. Dwelling area, insulation of the house, climatic condition of the area, are the main influencing factors.

To have a rough estimation about the system which its operation depends on climatic condition, we need to calculate the functions in different probable climatic conditions. With this logic, later we will divide Europe into ten climatic sub-categories, and for each climatic subcategory, a city with the most relevance chosen.

Moreover, two type of houses selected, based on previous studies as the European most common residential dwelling.

The final aim of this study is to calculate the emission production, due to implementing the solar thermal system, for space heating and DHW.

1.4 Introduction to Environmental impact

Renewable energy directives of European energy commission established an overall policy for EU to produce and promote at least 20% of its total energy demand by renewable energy sources up to 2020, (at least 27% up to 2030). The proven environmental issues regarding the burning of fossil fuel, like global warming, and the ecological outlook of EU, guides the EU states to support and subsidize the extent of renewable energy usage.

There is a difference between emission production of fossil fuel-based systems and systems based on renewable energy sources. The dominant pollutant part of fossil fuel combustion systems is the combustion process, on the other hand, for renewable energy conversion systems, like solar thermal heat generation system, the manufacture of the system itself is the primary source of pollution. The emission produced by combustion systems, distribute during the lifetime of the system almost equally, but for the solar thermal system, almost all the emission production happens during the processes before system installation.

1.5 Previous Literature

Several studies, papers, and reports have been conducted and published in the past, which analyzed the environmental performance of solar thermal panels. Many studies tried to compare the energy savings of solar thermal systems instead of fossil systems, by calculating the avoided emissions (Rey-Martínez, 2007; Hobbi, 2009; Martinopoulos G. 2018)[3,4,5]. In this method, the aim is to maximize the efficiency of the system by increasing the solar fraction. Several studies provided the bill of explicit material used in the solar thermal system (Beccali, 2005)[6] and explained the environmental impact by material breakdown and manufacturing. Among them, there are few studies which calculate the environmental impact of using the solar thermal system with considering both of solar thermal system manufacture, raw material, and energy production during its lifetime and provide the emissions per unit of energy produced.(Greening & Azapagic, 2014)[7]

1.6 Problem Statement

Previous studies in estimating the environmental impact per unit of energy production, assume the annual energy production by using annual average irradiation per square meter [7] without discussing the usability of this energy, so the results are not taking into consideration the seasonal variation of production (due to climatic condition and solar irradiation) and demand (due to temperature variation). As we will explain later, the peak of solar thermal system heat production and heating demand in a residential building are polar, the production peak is in summer, and maximum demand is in winter. Previous studies results are reliable just in the case of no extra (over demand) heat production in summer (or seasonal heat storage system).

When a system designed as combi system, to use as space heating and hot water application, in order to have adequate heating coverage during cold seasons, we are inevitable to implement higher collector areas, which lead overproduction in summer, this is when the previous study results are not applicable anymore.

This study aims to calculate the emission production and global warming potential of implementing the solar thermal system, in a residential dwelling, with taking into consideration of seasonal effect, in production and demand.

2 Solar thermal systems

The solar thermal system is a configuration, to the conversion of sunlight radiation energy into thermal energy. This energy conversion is based on absorption of solar radiation by a surface. The amount of absorbed energy is up to the total amount of incident solar spectral as well as the absorbance efficiency of the surface material.

The main components of such a system can be divided into three main categories:

1- Collector, collect the incident solar energy and convert to heat
2- Storage, store the heat in order to use when required
3- Distribution, the system to supply the heat to the final user (i.e., DHW or space heating)

Part of solar radiation is lost when passes through the atmosphere, because of absorption, scattering, and reflection by the water vapor, clouds, and pollution in the air. The total solar irradiation on a surface on earth may consist three components, direct beam of irradiation straight from the sun to surface G_b, diffused irradiation arriving from all directions which scattered by the atmosphere G_d, and reflected irradiation from other objects surrounding G_r. So the total irradiation expressed as equation [8]

$$G=G_b+G_d+G_r. \tag{1}$$

The radiation which reaches the surface, either reflected or absorbed. The reflectance factor ρ and absorbance factor α is the measuring tool to determine the share of absorbance-reflectance. The sum of this two factors must be equal to unity ($\rho+\alpha=1$).

The rate of energy absorbance by the surface is $G\alpha$. As the radiation hit the surface, it becomes warmer, the rate of heat loss depends on the surface conductance (h_0) and the temperature difference of surface and air T_s-T_a. If we have an absorber supplied with heat transfer media, then this loss of heat can be transmitted to the media. The rate of energy input becomes equal to heat transferred to media, in an equilibrium condition,

$$G\alpha=h_0(T_s-T_a) \tag{2}$$

so the maximum surface temperature is

$$T_s=T_a+(G\alpha/h_0) \tag{3}$$

The heat transfer media and the shape of the absorber categorize the collectors, flat plate collector (FPC), evacuated tube collector (ETC) and concentrating collectors are three main solar thermal collector categories. [8]

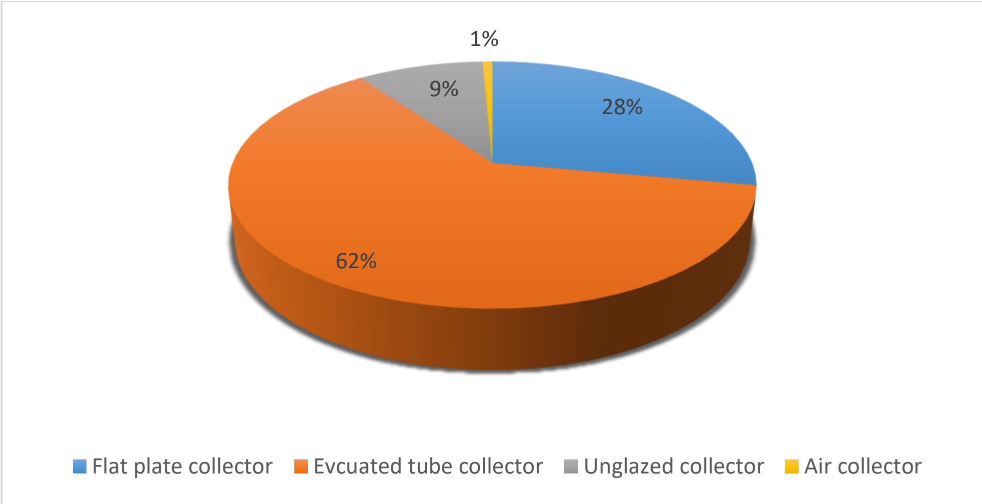

Figure 3 Distribution of the total installed capacity in operation worldwide by collector type in 2011.[9]

China, with the installation of massive capacity of evacuated tube collectors, manipulates the total world distribution of solar collector type. In Asia except for China, middle east and north Africa, Latin America, and Europe, the dominant solar thermal collector is flat plate collector. The statistics in Europe shows that, in 2015, 81.5% of the newly installed solar thermal collectors were flat plate collectors, followed by ETC with 15.6% (Figure 3&Figure 4). [1]

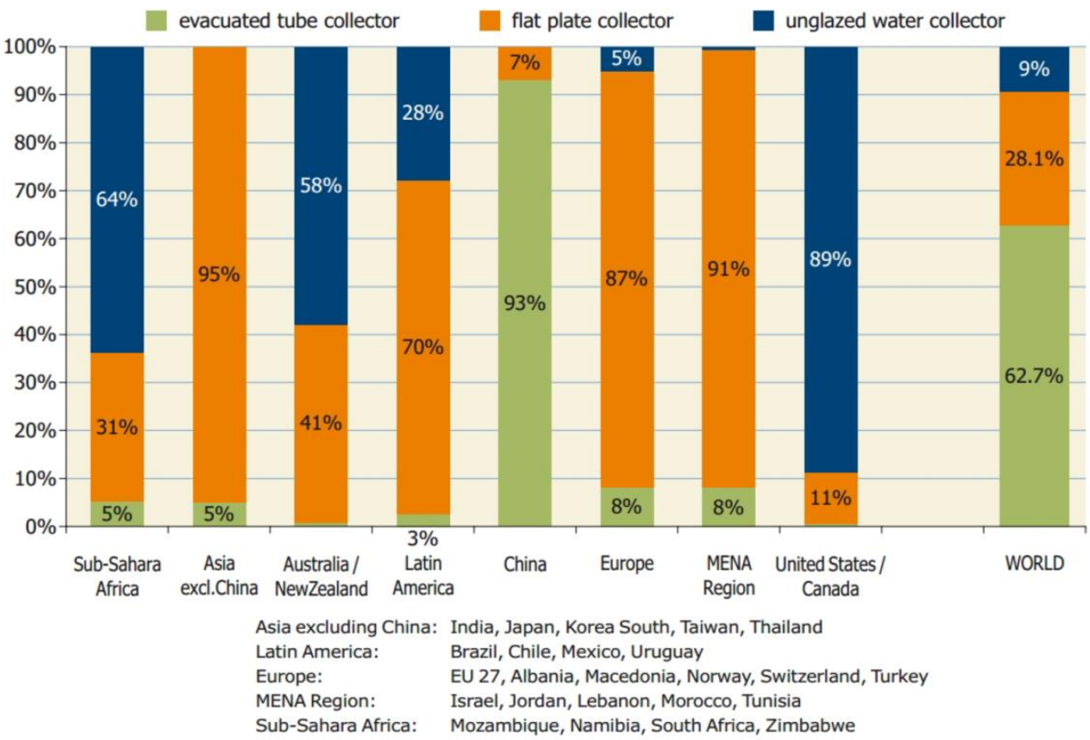

Figure 4 Distribution by type of solar thermal collector for the total installed water collector capacity in operation by the end of 2011[9]

2.1 Flat plate collector (FPC)

The most fundamental and most popular type of solar thermal collector in Europe is FPC, consist of an absorber plate in a metallic casing, equipped with one or two layers of transparent cover (mostly low iron glass) which called glazed FPC, and insulation behind the absorber plate. Flat plate collector media can be liquid or gas (air). A typical liquid flat plate solar collector consists of a black absorber, which converts the solar irradiation into heat, and channels or pipes which heat transfer fluid (HTF) is flowing through. The back side of the absorber plate is insulated, and the front side is covered by the glazing, that allows the solar radiation to pass, but reduce the heat losses to atmosphere. [8]

Absorber plate can be covered by a different kind of selective black color, and selective coatings to reach the higher absorbance efficiency. The heat transfer fluid pipes are into contact with absorber plate, either welded or corrugated inside the absorber body.

Heat transfer fluid is mostly a mixture of 60% water and 40% polypropylene (or ethylene) glycol.

The main advantages of using FPC is:

1- Easy to manufacture
2- Low cost
3- Collect both beam and diffuse radiation
4- Permanently fixed (no sophisticated positioning or tracking equipment is required)
5- Little maintenance

2.2 Evacuated tube collector

Evacuated tube collector (ETC) or vacuum tube collector, converts solar energy to heat based on condensing and evaporating cycle of heat transfer fluid. The structure of this collector is (at least) 3-layer tube; the outer layer is a glass tube to let the solar radiation hit the inner absorber, the space between absorber and glass tube is vacuumed to minimize the heat loss. The core section of the collector is the copper pipe, which contains some heat transfer fluid (i.e., water or ethanol and no air inside), with increasing the copper pipe with heat transfer via absorber, the heat transfer fluid evaporates and vapor flows to the upper part of the pipe, where it condenses and release its latent heat to another fluid. The condensed fluid returns to the bottom of the pipe and the process repeated(Figure 5).

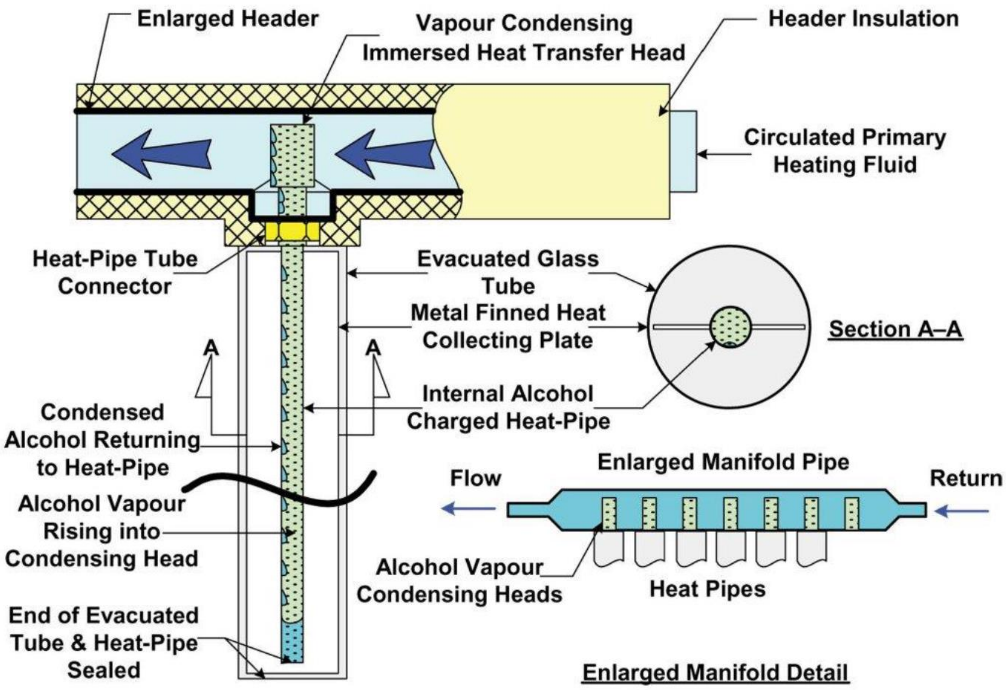

Figure 5 ETC heat transfer system [10]

2.3 Storage tank

Heat production and consumption is not an online network, so a storage system needed to collect the produced heat in the collector, in order to keep it available when needed. In most of the heating systems, the heat storage tank is a water tank with insulation, which absorbs the heat produced by a heat source and connected to users (Figure 6).

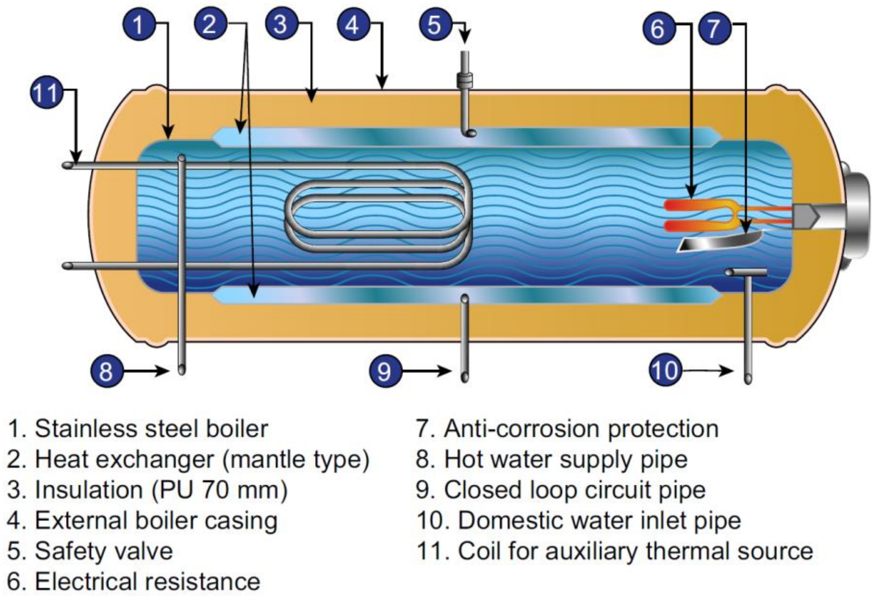

Figure 6 Cross section of a typical hot water storage tank [8]

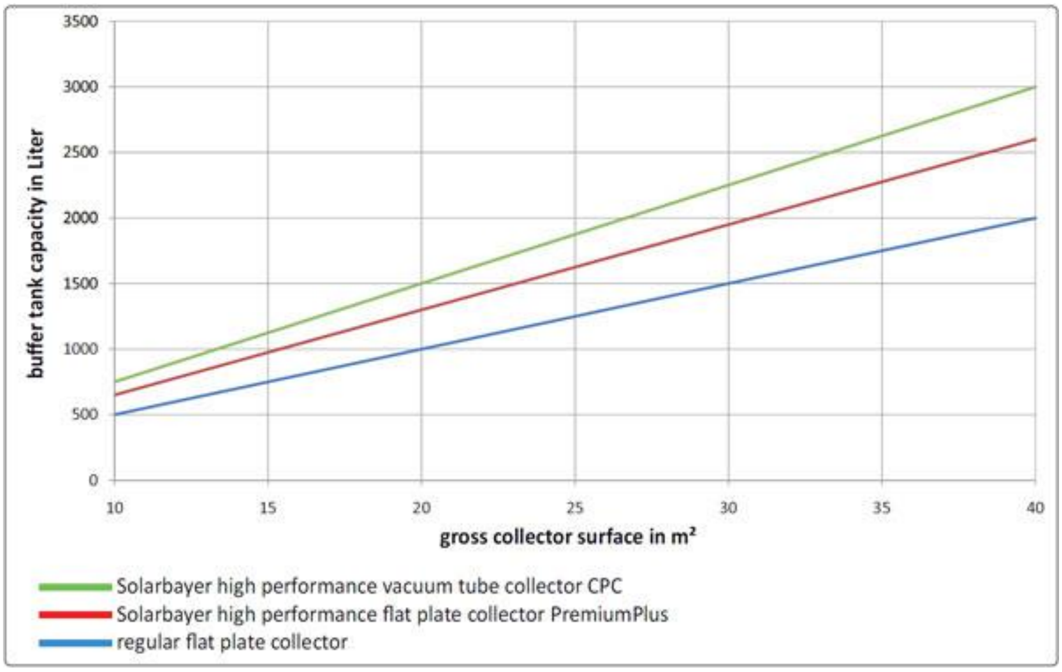

Figure 7 tank size chart [11]

The size of the hot water tank has to be matched to the size of the collector area. If the tank capacity is too big, no useful temperature will be achieved, on the other hand, with the tiny tank the solar energy is not used efficiently. The above graph is guidance to select the suitable size of tank regarding the surface area of the collector for FPC and Vacuum tube collectors (Figure 7).

In this report, for ease of calculation, we assume for all studied systems with different collector areas we use 1000L tank for heat storage.

2.4 Auxiliary Heating systems

Besides the main components of the solar thermal system, collector and storage tank, the system consists of other equipment which depends on the application of the system, hot water for sanitary use, space heating, or both.

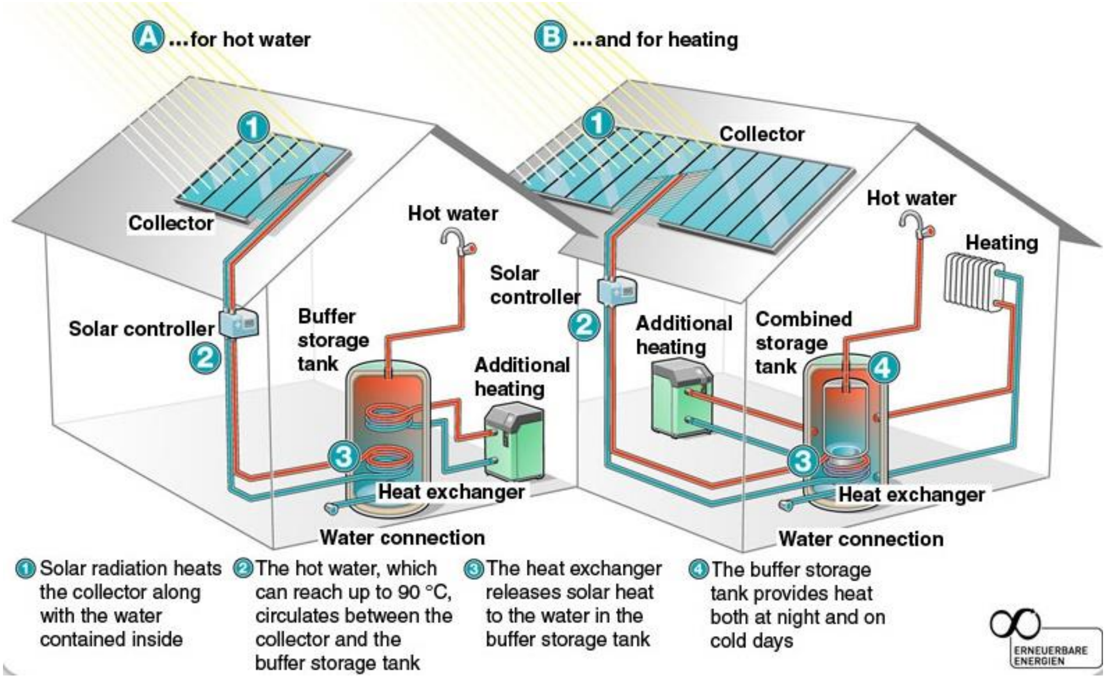

Figure 8 Solar thermal system for DHW versus Solar combi system [12]

According to the application, size of the system, and general configuration of the system, it can consist of one or several, heat exchangers, pumps, expansion vessels, valves, and piping. In the case of space heating, hot water radiator or underground heating pipes is also needed.

The studied system in this report is a combination of domestic hot water for sanitary uses (DHW) and space heating for a residential building. This type of solar thermal system is known as “solar combi-systems” (Figure 8).

In the simplest type of combi system, the same heat transfer fluid passes through the collector and space heating system (forced by a pump), and a heat exchanger for DHW. A backup system (e.g., electric or natural gas) is also needed to fulfill the demand in cold seasons.

3 Reference house

3.1 General background

This chapter aims to collect data regarding the typical European residential dwelling, to calculate the heating and domestic hot water (DHW) demand which can cover by the solar thermal system.

3.2 Building types

According to statistics of the statistical office of the European Union located in Luxemburg, in 2016, 41.8% of the population in EU-28 lived in flats, almost one quarter (23.9%) lived in semi-detached houses and more than one third (33.6%) in detached houses. In Spain, Latvia, Switzerland, and Estonia, more than 60% of people living in flats, also in the most populated country of EU, Germany, 58% of people are living in flats. On the other hand, semi-detached houses, is the most popular dwelling in the UK (60%), Netherland (58%) and Ireland (52%). The former Yugoslav republics plus Romania, Hungary, Croatia, and Slovenia, also known as the counties with the highest population of their country living in detached houses (Figure 9). [1]

So, in general, dwellings divided into three categories. Stand-alone house or detached house, on private ground, with distance (at least a few meters) to neighbors. Semi-Detached dwellings or mirror houses, which are common in the UK, are two detached houses with one common side wall. Moreover, the apartment block is usually a multi-store, multi-family, building with common infrastructures.

One of the critical factors of comfort in houses is the floor area per dweller, which is characterized in EU legislation, the average floor area per dweller in EU countries is 42.56 m^2 per person. Also, the Eurostat in 2016 reported that the average resident's size of private households was 2.3 person. [1]

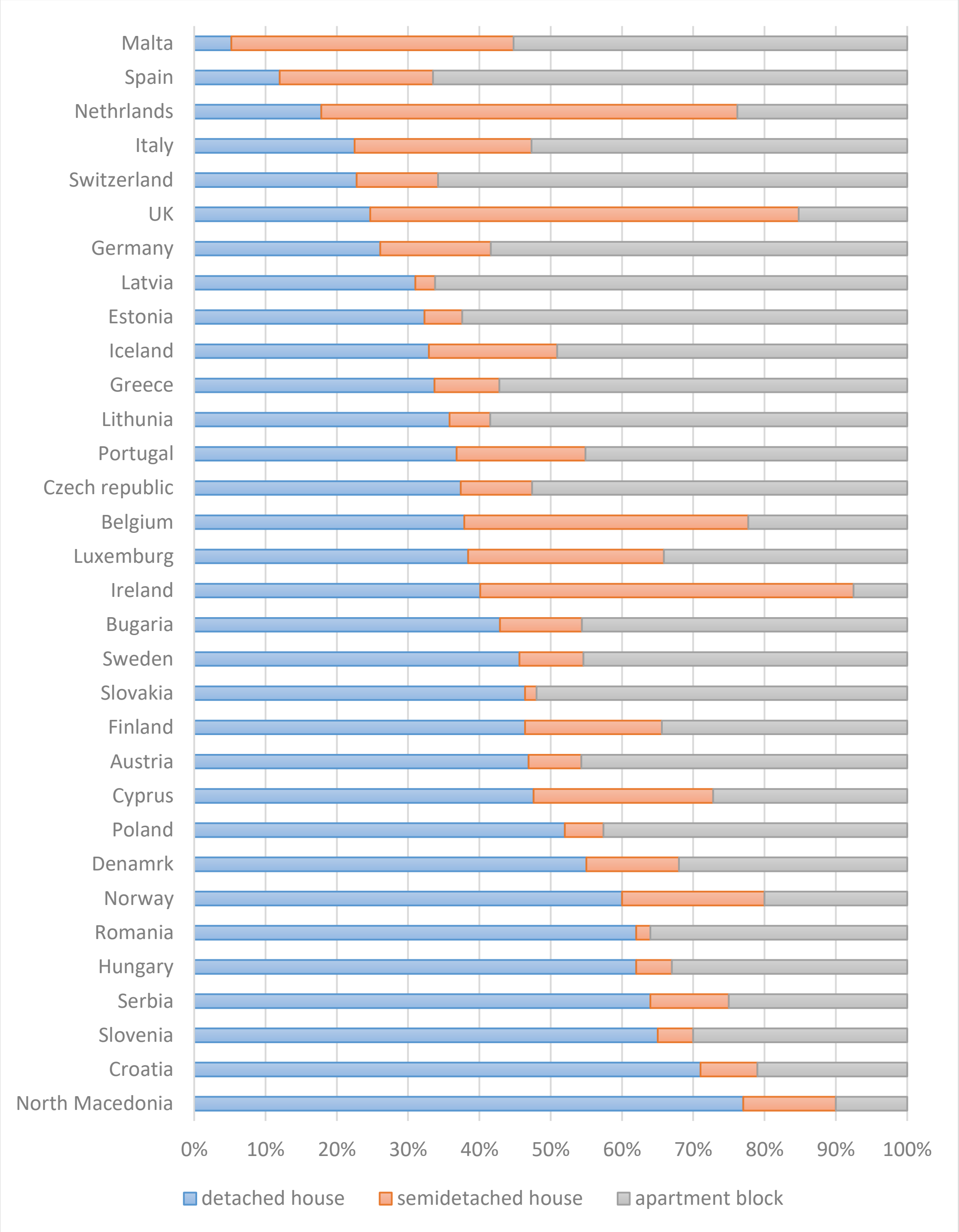

Figure 9 Distribution of population by dwelling type, 2016 [1]

Between 2012 and 2014 the ENTRANZE Project had been done by some European research centers with leading of Paolo Zangheri in Polytechnic of Milan to provide required data for policy making roadmap of RES (Renewable energy sources) penetration within the existing national building stocks. The objective part of the project was the dialogue with policymakers and experts, and it focuses on nine countries, which covers more than 60% of EU-27 building stock. The report provided an overview of the energy need for heating, cooling, and DHW for several building types, located in different European climate contexts. [2]

To define a model, which represent the majority of European houses, two type of buildings were investigated, a single family house, and an apartment block, in 10 different cities around Europe.

The single-family house is defined as a detached house, with the land area of 8.5 x 8.5 m, in 2 floors, with a total height of 6.4 m with characteristics of Table 1 and Figure 10.

Table 1 Fixed characteristics of the single house model.[2]

	N° of heated floor	**2**
Building geometry	S/V ratio	0.7 m²/m3
	Orientation: S/N	S/N
	Net dimensions of heated volume	8.5*8.5*6m
	Net floor area of heated zones	140 m²
	Area of S façade	51 m²
	Area of E façade	51 m²
	Area of N façade	51 m²
	Area of W façade	51 m²
	Area of Roof	72.25 m²
	Area of Basement	72.25 m²
	Window area on S façade	25%
	Window area on E façade	7%
	Window area on N façade	25%
	Window area on W façade	7%
Internal Gains	People design level	50 m²/person
	Lighting design level	3.5 W/m²
	Appliances design level	4 W/m²

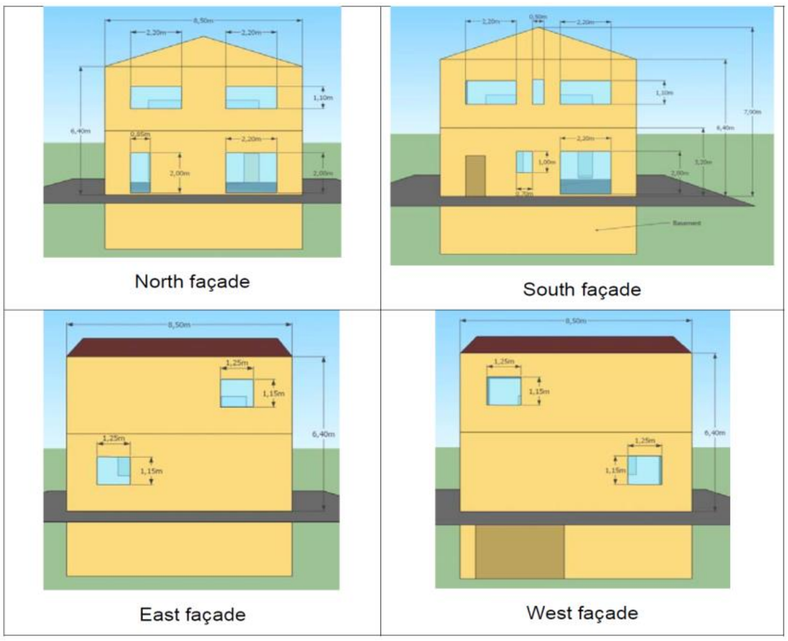

Figure 10 Prospects of the single house model [2]

The other type of building we study is an apartment block. This reference apartment block has four floors, composed of 12-16 flats and its conditioned area is about 1000m² .Figure 11Table 2 Fixed characteristics of the apartment block model [2].

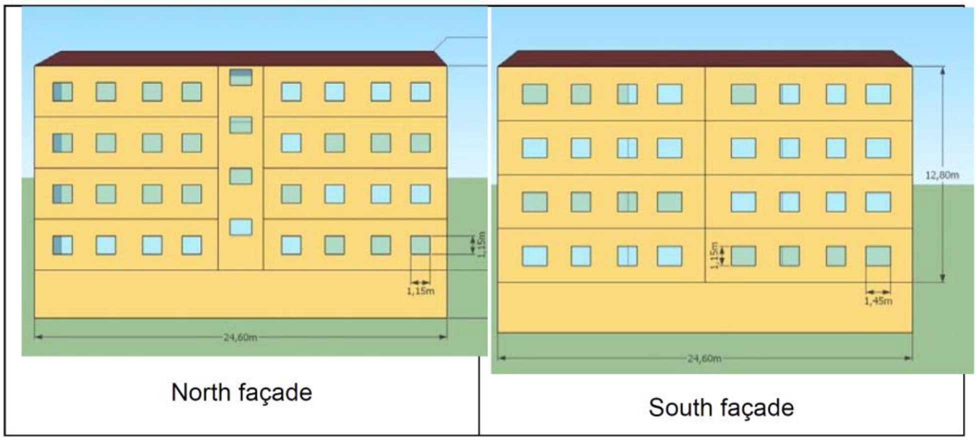

Figure 11 Prospects of the apartment block model [2]

Table 2 Fixed characteristics of the apartment block model [2]

Fixed attributes of the single house model.		ES, IT, FR	RO, AT, CZ, DE, FI
	N° of heated floor	4	
	S/V ratio	0.33 m²/m³	
	Orientation: S/N	S/N	
	Net dimensions of heated volume	24.6*11.2*12.8m	
	Net floor area of heated zones	990 m²	
	Area of S façade	315 m²	
	Area of E façade	143 m²	
	Area of N façade	315 m²	
	Area of W façade	143 m²	
	Area of Roof	54 m²	
	Area of Basement	54 m²	
	Window area on S façade	15%	30%
	Window area on E façade	0%	0%
	Window area on N façade	15%	30%
	Window area on W façade	0%	0%
Internal Gains	People design level	25 m²/person	
	Lighting design level	3.5 W/m²	
	Appliances design level	4 W/m²	

3.3 Climate contexts

Solar radiation is the dominant driving energy of the solar thermal system, So the climatic condition of the site, directly affect the performance of the system — the sunny sites, near the equator, gather more solar energy. Moreover, the temperature of the site dictates the heating demand of the house, which is one of the most important factors to design a solar thermal system. Based on the climatic condition of Europe, ten groups of climate characteristics were selected, and according to this characteristics, ten cities with most relevance were chosen to further studies (Table 4 and Table 11).

Table 3 Characterization of the ten selected climates [2]

Context	Climatic characterization	Relevance
Seville (ES)	Mediterranean climate (hot summer subtype) with shallow climatic cooling potential (extreme summer conditions)	Medium
Madrid (ES)	A semi-arid climate with low climatic cooling potential	High
Rome (IT)	Mediterranean climate (warm summer subtype) with medium climatic cooling potential	High
Milan (IT)	A humid subtropical climate with medium climatic cooling potential	High
Bucharest (RO)	Humid continental (hot summer subtype) / Subarctic climate with medium climatic cooling potential	High
Vienna (AT)	Humid continental climate (warm summer subtype) with high climatic cooling potential	High
Paris (FR)	Oceanic climate with very high climatic cooling potential	High
Prague (CZ)	Humid continental climate (warm summer subtype) with high climatic cooling potential	High
Berlin (DE)	Humid continental climate (warm summer subtype) with high climatic cooling potential	High
Helsinki (FI)	Humid continental / Subarctic climate (extreme winter conditions)	Medium

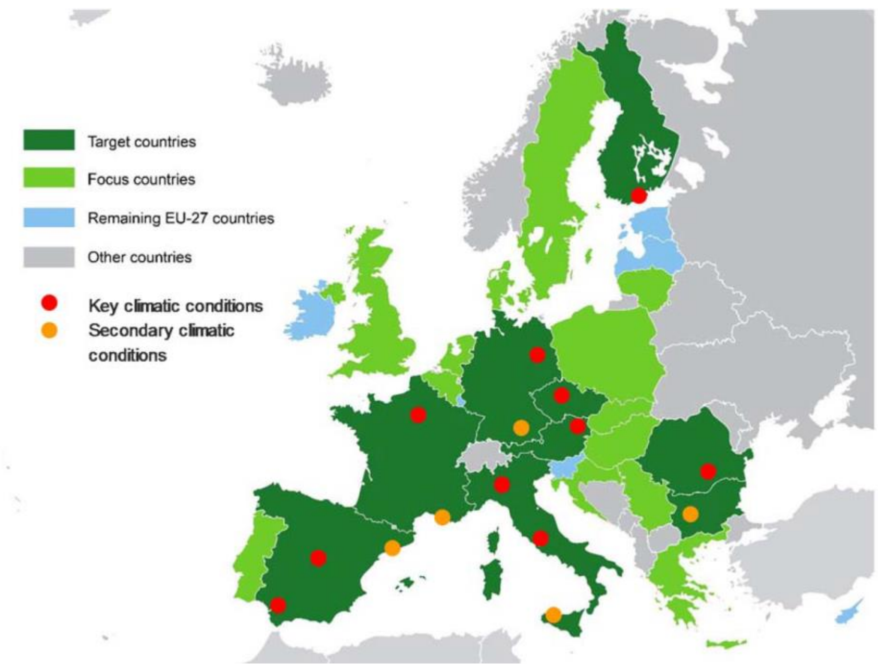

Figure 12 Key and secondary weather conditions selected for the study [2]

To calculate the heating demand of the house, we need to assume the indoor conditions regarding comfort which performs for residential buildings at 20°C in winter and 26°C in summer.

The final results of the energy demand of a single family house and an apartment block according to the Entranze project are presented in tables 5 and 6 below, based on a monthly basis per KWh/m². [2]

Noticeable is, that, the building structure for all studied cities considered the same and fixed for both single-family house and apartment block, but the other factors, like volumes of walls and roof and basement and the insulation level, is differing country to country depends on the style of the building of the region.

Table 4 Summary of simulated energy needs for heating, cooling and DHW for the single house base cases KWh [2]

Country	City	End use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ES	Seville	Heating	11.2	6.2	2.6	1.5	0.1	0	0	0	0	0.1	5.2	9.8
		DHW	1.2	1.1	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2	1.2
ES	Madrid	Heating	25.9	18.2	8.5	6.2	0.6	0	0	0	0	3.9	14	26.6
		DHW	1.3	1.1	1.3	1.2	1.3	1.2	1.3	1.3	1.2	1.3	1.2	1.3
IT	Rome	Heating	18.8	11.7	7.3	2.1	0.3	0	0	0	0	2.8	7.5	16.7
		DHW	1.3	1.1	1.3	1.2	1.3	1.2	1.3	1.3	1.2	1.3	1.2	1.3
IT	Milan	Heating	39.9	30.1	14.2	8	1.1	0	0	0	0	7.2	23.4	37
		DHW	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
RO	Bucharest	Heating	45.5	30.6	21.1	6.6	1.5	0	0	0	1.5	11.7	28.5	42.1
		DHW	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
AT	Vienna	Heating	43.4	35.5	21.3	10	2.1	0.33	0	0	1.9	12.3	29.2	43.5
		DHW	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
FR	Paris	Heating	35.1	29.5	21.8	11.6	3.2	0.5	0	0	2.5	11.6	25.9	34.2
		DHW	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
CZ	Prague	Heating	48.5	40.1	28	14.9	5.3	0	0	0	5.2	18.5	35.9	43
		DHW	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
DE	Berlin	Heating	33.4	30	21.2	9.5	3.2	0	0	0	2.2	11.4	24.9	32.9
		DHW	1.3	1.2	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3	1.3
FI	Helsinki	Heating	31.2	26.9	20.9	9.8	1.6	0	0	0	4.2	13.3	26.4	31
		DHW	1.4	1.3	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4	1.4

Table 5 Summary of simulated energy demand for heating, cooling and DHW for the apartment block cases kWh. [2]

Country	City	End use	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
ES	Seville	Heating	6.8	3.9	1.8	1.1	0.2	0	0	0	0	0	3	5.7
		DHW	1.8	1.7	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
ES	Madrid	Heating	15.9	11.3	6.1	4.7	0.3	0	0	0	0	2.3	8.3	15.8
		DHW	1.9	1.7	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
IT	Rome	Heating	11	7.2	5	1.7	0.2	0	0	0	0	1.5	4.1	9.5
		DHW	1.9	1.7	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
IT	Milan	Heating	24.9	19.3	9.3	5.2	0.7	0	0	0	0	3.9	13.7	23
		DHW	2	1.8	2	2	2	2	2	2	2	2	2	2
RO	Bucharest	Heating	28.4	18.8	13.1	4.3	1.6	0.4	0.3	0.5	1.5	6.8	17.2	26.1
		DHW	2.1	1.9	2.1	2	2.1	2	2.1	2.1	2	2.1	2	2.1
AT	Vienna	Heating	27.8	22.5	13.4	6.7	2.2	1.2	0.9	0.9	1.9	7.4	18.1	23
		DHW	2.1	1.9	2.1	2	2.1	2	2.1	2.1	2	2.1	2	2.1
FR	Paris	Heating	28.7	24.9	18.8	10.3	3	0.5	0	0	2.1	9.2	20.8	27.6
		DHW	2.1	1.9	2.1	2	2.1	2	2.1	2.1	2	2.1	2	2.1
CZ	Prague	Heating	24.3	19.8	13.3	6.8	2.6	0.7	0.9	0.7	2.2	8	17.5	21.1
		DHW	2.1	1.9	2.1	2	2.1	2	2.1	2.1	2	2.1	2	2.1
DE	Berlin	Heating	26.2	23.5	16.5	8.2	3.5	1	1.1	1.1	2.3	8.8	19	25.8
		DHW	2.1	1.9	2.1	2	2.1	2	2.1	2.1	2	2.1	2	2.1
FI	Helsinki	Heating	25.3	21.8	16.8	8.1	2	1	1.2	0.7	3.1	10.3	21.4	25.3
		DHW	2.2	2	2.2	2.1	2.2	2.1	2.2	2.2	2.1	2.2	2.1	2.2

The results of this research will be the design input of the solar thermal system to cover heating and DHW demand. The results are in kWh per square meter of heating area of the house, which can be extended to all preferable kind of residential dwelling.

3.4 Collector Area

Other than the collector type, climatic condition, and site performance, one of the determinative elements in the performance of the solar thermal system is the collector area. As much as more collector area, more heating energy will have collected. On the other hand, in the design of the system, we need to take into account the balance of production and demand in all seasons. The over-demand production in summer is one of the reasons that we cannot use high area of the collectors, in areas with high solar radiation potential.

Using seasonal heat storage systems can be a remedy to overcome the energy cut in summer, and improve the overall performance of the system.

To study the effect of using higher collector area on energy production, and understand the environmental impact of using higher collector area, in this research, for all studied climatic context, the collector area of 10-40 m^2 will use in calculations.

4 Energy calculation

4.1 F-chart method

The f-chart method is a method to estimate the long-term thermal efficiency of a solar-thermal system. The f-chart method applies to the heating of a building where the minimum temperature for energy delivery is approximately 20 degrees centigrade. This method is applicable for both liquid and air systems.

The method will provide a means for estimating the fraction of a total heating load that will be supplied by solar energy for a given solar heating system.

The main design variables of the estimation are the area of the collector, and the other variables are collector type, the volume of the storage tank, flow rate, and heat-exchanger size and load. F-chart method is a correlation between the results of hundreds of simulations of solar heating systems(Figure 13). [22]

The result of the method will provide us the f, fraction of heating load (for both space heating and domestic hot water production) supplied by solar energy, as a function of two dimensionless parameters. First one is related to the ratio of collector losses to heating load, and the second one is related to the rate of absorbed solar radiation to heating loads.

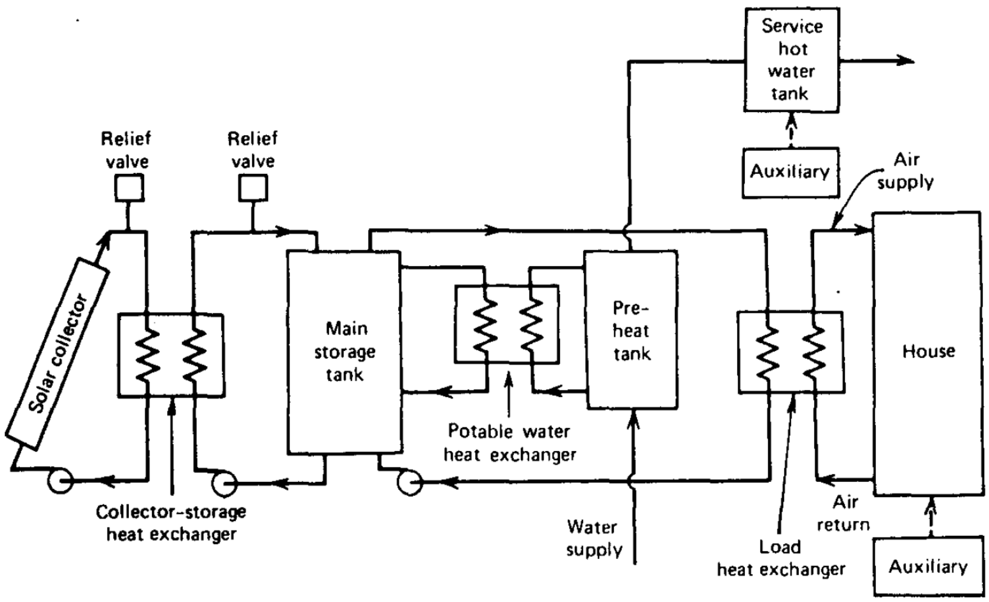

Figure 13 Schematic of the solar heat generation system for space heating and DHW [22]

Two dimensionless factors are:

$$X = \frac{A_c F_R' U_L (T_{ref} - \overline{T_a}) \Delta t}{L} \quad \textbf{(1)}$$

$$Y = \frac{A_c F_R' (\overline{\tau\alpha}) \overline{H_T} N}{L} \quad \textbf{(2)}$$

Where:

A_c=Collector area (m^2)

F_R'=collector heat-exchanger efficiency factor

U_L= collector overall loss coefficient (W/m^2-C)

Δt = total number of seconds in the month

T_a= monthly average ambient temperature (C)

T_{ref}= an empirically derived reference temperature (100 C)

H_T= monthly average daily radiation incident on the collector surface per unit area (J/m^2)

L= monthly total heating load for space heating and hot water (J)

N=days in month

$\overline{\tau\alpha}$=monthly average transmittance-absorptance product

We can write the equations as:

$$X = F_R U_L * \frac{F_R'}{F_R} * \left(T_{ref} - \overline{T_a}\right) * \Delta t * \frac{A_c}{L} \quad \textbf{(3)}$$

$$Y = F_R (\tau\alpha)_n * \frac{F_R'}{F_R} * \frac{(\overline{\tau\alpha})}{(\tau\alpha)_n} * \overline{H_T} N * \frac{A_c}{L} \quad \textbf{(4)}$$

Which the terms $F_R U_L$ and $F_R(\tau\alpha)_n$ are the collector specifications and obtained from collector test results. The ratio $\frac{F_R'}{F_R}$ is the indicator of the penalty in collector performance because the heat exchanger cause the collector to operate at higher temperature than it otherwise would. It can be found from the graph below (Figure 14) as a function of $\frac{(\dot{m}C_p)min}{(\dot{m}C_p)c}$ on both sides of heat exchanger, depends on the percentage of glycol used (usually around 0.7-0.9), the overall fraction of $\frac{F_R'}{F_R}$ is usually more than 0.9

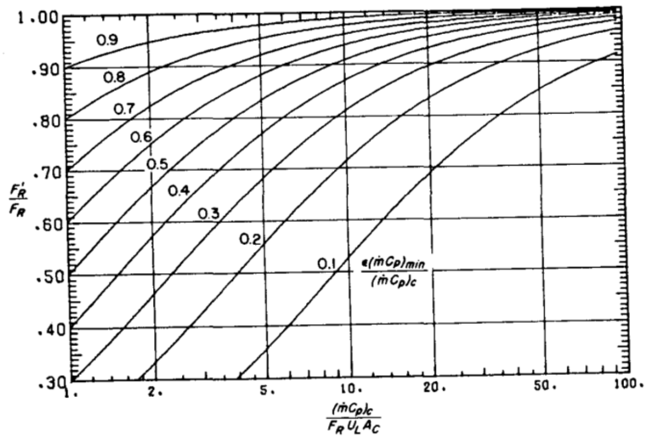

Figure 14 heat exchanger correction factor [24]

the dependence of absorption and transmission on the angle of incidence of the incident radiation is expressed by The ratio of $\frac{(\overline{\tau\alpha})}{(\tau\alpha)_n}$ to ease of use [24]

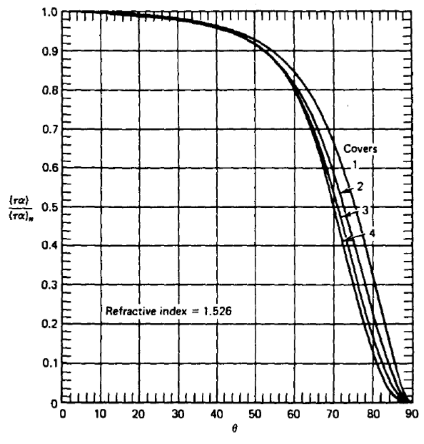

Figure 15 typical $\frac{(\overline{\tau\alpha})}{(\tau\alpha)_n}$ curve for 1-4 covers [22]

Also, the two values to describe the solar collector, the solar collector thermal performance curve slope (F_RU_L) and intercept ($F_R(\tau\alpha)$) which are standard collector specifications which provided by factory tests. The value of this parameters are specific for each collector technology, the table below (Table 6) shows the average value of this parameter for the two most popular technology of solar-thermal collectors, flat plate collector, and vacuum tube collector. [23]

Table 6 collectors specification [23][22]

Collector description	***FR(τα)n***	***FRUL***
Flat-plate single glazed	**0.6675**	**5.5**

Evacuated, selective surface 0.7000 3.3

The tilt angle of the panel is considered equal to the city longitude.

The parameter H_T or monthly average daily radiation incident on the collector surface per unit area for the tilted collector

$$H_T = (H - H_D)R_b + H_D\left(\frac{1+\cos\beta}{2}\right) + H\rho(\frac{1-\cos\beta}{2}) \quad \textbf{(5)}$$

Which H is the global monthly average daily radiation incident on the horizontal collector, and H_D is the monthly average daily diffused radiation incident on the horizontal collector surface, β is the tilted angle of the surface and ρ is ground reflectance which assumed constant (=0.2), R_b is known as extraterrestrial radiation on the tilted surface to that on a horizontal surface for each month [22][23]

$$R_b = \frac{\cos(\phi-\beta)\cos\delta\sin\omega' + \left(\pi/_{180}\right)\acute{\omega}\sin(\phi-\beta)\sin\delta}{\cos\phi\cos\delta\sin\omega + \left(\pi/_{180}\right)\omega\sin\phi\sin\delta} \quad \textbf{(6)}$$

The parameter ω is solar hour angle and $\acute{\omega}$ is the sunset hour angle for the tilted surface, φ is the latitude of the location, and δ is solar declination, the related equations are presented below

$$\delta = 23.45\sin\left(360\frac{284+n}{365}\right) \quad \textbf{(7)}$$

$$\omega = \cos^{-1}(-\tan\phi\tan\delta) \quad \textbf{(8)}$$

$$\acute{\omega} = \min(\omega\ \&\ \cos^{-1}(-\tan(\phi-\beta)\tan\delta) \quad \textbf{(9)}$$

The weather data files which collected from the Energyplus contains the daily and monthly average data for the horizontal surface of direct and diffused irradiation plus the global average data. Parameter n is the day of the year, which counts continently from the first of January.

Relation of X and Y and the solar fraction of the load is explained by the curve fit equation:

$$f = 1.029Y - 0.065X - 0.245Y^2 + 0.0018X^2 + 0.0215Y^3 \quad \textbf{(10)}$$

F is indicating the fraction of the monthly total load supplied by the solar space and water heating system. Heat demand of the end user is in the denominator of X and Y, this fraction is reliable when a rational demand of the system exists, when the demand is deficient, for example in summer, solar fraction moves to infinity.

4.2 The capacity factor of solar thermal energy

In all the studied cities, and with 5-40 m^2 of the solar collector, the hot water demand from May to August was fully supported by the solar thermal system, but the coverage of space heating depends on the climatic condition of the city and the solar radiation potential are different.

Apart from the cities like Seville, Madrid, Rome, and Thessaloniki, which does not have cold winters, in other cities of the etude, from November to February, the share of the solar system in the load is almost zero.

Table 7 annual space heating and DHW coverage per FPC area for a single family house

	solar flat plate collector area m²							
	5	10	15	20	25	30	35	40
Seville	34.4%	48.1%	57.4%	64.3%	69.9%	74.5%	78.2%	81.4%
Madrid	14.5%	22.1%	28.4%	33.6%	38.0%	41.7%	45.1%	48.1%
Rome	18.2%	26.4%	32.7%	37.9%	42.3%	46.1%	49.6%	52.5%
Milan	7.1%	10.5%	13.3%	15.7%	17.9%	19.9%	21.7%	23.4%
Bucharest	7.2%	11.0%	14.0%	16.6%	18.9%	21.0%	22.8%	24.6%
Vienna	5.3%	8.2%	10.3%	12.1%	13.8%	15.2%	16.4%	17.6%
Paris	5.4%	8.6%	11.0%	12.9%	14.7%	16.2%	17.8%	19.0%
Prague	3.5%	5.7%	7.5%	9.0%	10.4%	11.7%	12.8%	13.8%
Berlin	5.0%	7.9%	9.9%	11.6%	13.0%	14.4%	15.6%	16.5%
Helsinki	4.8%	7.4%	9.2%	10.7%	12.1%	13.3%	14.5%	15.6%
Thessaloniki	14.0%	21.2%	27.1%	32.0%	36.1%	39.6%	42.7%	45.5%

Table 8 annual space heating and DHW coverage per ETC area for a single family house

	solar vacuum tube collector area m²							
	5	10	15	20	25	30	35	40
Seville	39.3%	54.9%	65.3%	73.8%	80.7%	85.8%	89.3%	92.0%
Madrid	17.1%	26.7%	34.7%	41.3%	46.4%	50.8%	54.6%	57.9%
Rome	21.6%	32.3%	40.2%	46.9%	52.3%	57.0%	60.8%	64.0%
Milan	9.0%	13.7%	17.7%	21.4%	24.7%	27.7%	30.4%	32.8%
Bucharest	9.0%	14.0%	18.1%	21.7%	25.1%	27.9%	30.5%	33.0%
Vienna	6.8%	10.7%	13.6%	16.1%	18.3%	20.4%	22.3%	24.1%
Paris	7.2%	11.5%	15.0%	17.9%	20.3%	22.5%	24.6%	26.5%
Prague	4.7%	7.6%	10.2%	12.4%	14.4%	16.2%	17.7%	19.1%
Berlin	6.8%	10.5%	13.6%	16.0%	18.0%	19.8%	21.4%	22.9%
Helsinki	6.5%	9.7%	12.2%	14.5%	16.5%	18.3%	19.9%	21.3%
Thessaloniki	16.6%	25.7%	33.4%	39.8%	44.5%	48.7%	52.2%	55.2%

Table 7 shows the percentage of the total heating load demand of a single family house which can be supplied by the solar thermal system, with the single glazing flat plate collector, with an area of 5 to 40 m^2. For the Mediterranean cities, which does not have severe winters, and a mostly sunny sky, a significant share of total energy demand can be covered by the solar thermal system. In Madrid, with 30m^2 of flat plate collector, it is estimated that more than 40% of overall demand could be covered. On the other hand, northern regions, due to weak solar irradiation, and cloudy sky, this percentage can be as low as 13% for Helsinki or 11% for Prague.

By replacing the flat plate collector with evacuated tube collectors an increase in supplied heat is observed, due to better performance of these collectors. For the same area of the collector area, with vacuum tube collector in Milan, 50% of the demand and in Helsinki 18% would be supplied.

For the apartment block, the energy demand for hot water and space heating is higher, because of more area, and more residents, so the coverage percentage is also less.

Table 9 annual space heating and DHW coverage per FPC area for an apartment block

	Solar flat plate collector area m²							
	5	10	15	20	25	30	35	40
Seville	10.0%	18.8%	26.4%	33.0%	38.6%	43.4%	47.1%	50.1%
Madrid	4.2%	8.1%	11.5%	14.6%	17.4%	19.8%	22.1%	23.9%
Rome	5.2%	9.9%	14.2%	17.9%	21.3%	24.3%	26.9%	29.2%
Milan	2.1%	4.1%	5.9%	7.5%	8.9%	10.2%	11.4%	12.5%
Bucharest	2.1%	4.0%	5.8%	7.5%	9.0%	10.5%	11.8%	13.0%
Vienna	1.4%	2.8%	4.2%	5.4%	6.6%	7.7%	8.7%	9.7%
Paris	1.1%	2.2%	3.2%	4.2%	5.1%	5.9%	6.7%	7.4%
Prague	1.1%	2.3%	3.3%	4.3%	5.3%	6.2%	7.0%	7.4%
Berlin	1.1%	2.1%	3.2%	4.1%	5.0%	5.9%	6.7%	7.5%
Helsinki	1.0%	2.1%	3.0%	3.9%	4.8%	5.6%	6.4%	7.1%
Thessaloniki	4.1%	7.9%	11.3%	14.3%	17.0%	19.4%	21.5%	23.3%

Table 10 annual space heating and DHW coverage per ETC area for an apartment block

	solar vacuum tube collector area m²							
	5	10	15	20	25	30	35	40
Seville	11.7%	22.0%	31.0%	38.7%	45.1%	49.5%	53.1%	56.3%
Madrid	5.1%	9.7%	13.9%	17.7%	21.1%	23.8%	26.1%	28.1%
Rome	6.4%	12.1%	17.3%	22.0%	26.2%	29.8%	32.6%	35.0%
Milan	2.7%	5.2%	7.5%	9.6%	11.5%	13.2%	14.7%	15.9%
Bucharest	2.6%	5.0%	7.3%	9.4%	11.4%	13.2%	14.9%	16.5%
Vienna	1.9%	3.6%	5.4%	7.0%	8.5%	9.9%	11.3%	12.6%
Paris	1.5%	2.9%	4.3%	5.6%	6.8%	7.9%	8.9%	9.9%
Prague	1.5%	3.0%	4.4%	5.8%	7.1%	8.3%	9.4%	10.5%
Berlin	1.4%	2.9%	4.2%	5.5%	6.7%	7.9%	9.0%	10.1%
Helsinki	1.4%	2.7%	4.0%	5.2%	6.4%	7.4%	8.5%	9.4%
Thessaloniki	5.0%	9.5%	13.6%	17.3%	20.6%	23.3%	25.4%	27.3%

5 Life Cycle Assessment

5.1 Methodology

Life Cycle Assessment (LCA) is a method to evaluate the environmental impacts of manufacture and operation of the target system (here solar thermal heat generation system, Figure 16) throughout whole life cycle of it, from resource extraction of raw material, processes, manufacture, energy use, transport, installation and use and finally disposal or recycling [7]. The methodology used in this study is coinciding with the ISO 14040 and ISO 14044, while the detailed solar thermal system has been studied through the software package OpenLCA 1.7.2, with the Ecoinvent 3.4 database. CML (v4.4 2015) method has been used to weight the environmental impacts throughout the study.

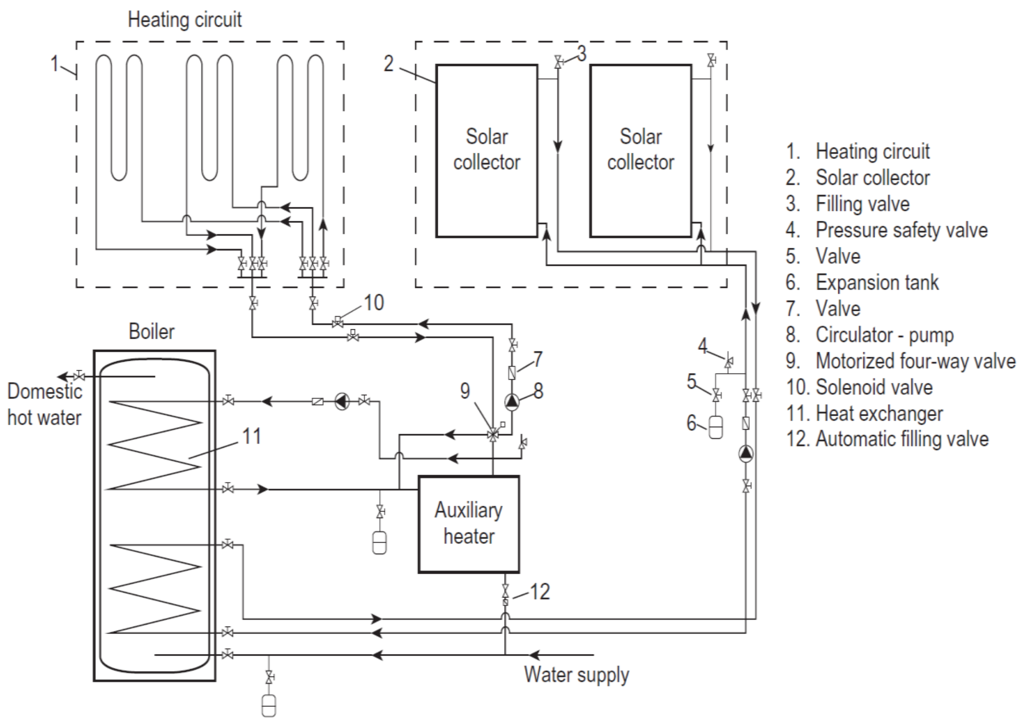

Figure 16 diagram of solar combi system [8]

5.2 Goal and scope

The Goal of this LCA study is to evaluate the environmental impact of using the solar-thermal system (flat plate collector and evacuated tube collector) for domestic hot water and space heating, in two reference houses discussed in chapter 3 in 10 climatic conditions in Europe.

Because this report aims to study the environmental impact of the solar thermal system, the common subsystems for domestic hot water and space heating are not involved, such as piping other than internal solar thermal system and radiators, they will discuss in next chapter.

In this study, the solar thermal system is breaking down to its components, such as solar thermal panel, hot water tank, pump, expansion valve and auxiliaries (piping, joints, valves, heat removal fluid).

Two types of solar thermal systems were studied, solar-thermal flat place collector, and solar-thermal evacuated tube.

5.3 Functional unit

For this study, it is possible to select different functional units, such as:

- A solar thermal system (system as a unit)
- A unit area of the collector
- Output energy unit

The functional unit of this LCA study is chosen to be the kWh of heat covered by a solar thermal system for space heating and domestic hot water of a single-family dwelling and an apartment block, but in the first phase we calculate the emissions per square meter of the solar thermal panel then we will translate it regarding the extracted heat from the system in different cities to reach the goal result.

5.4 System boundary

This research aims to study the solar thermal system under the cradle to grave perspective, so the boundaries of the system include the extraction process of raw material, metals, minerals, chemicals, fuel and processes for each input material to the related industry, leads to manufacturing the subsystem, such as panel, pump, auxiliary systems, support etc. Figure 17 shows the system boundaries of the studied system.

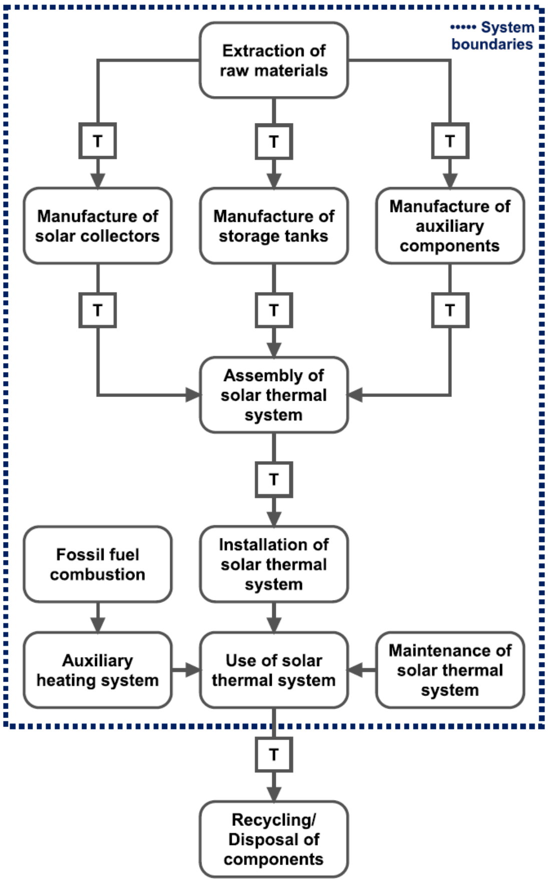

Figure 17 system boundary [7]

According to "renewables energy global status report 2018" (European Commission, 2018) China is the dominant player in the global solar panel production with 66% (90% for Asia). With good approximation, we assume that the planned system of this research is also made and assembled in China, then shipped from Shanghai (China) to Rotterdam port in the Netherlands, and finally transported by road to the final installation location.

The solar system manufacturing process is divided into three major sub-process, solar collector, storage tank, and auxiliary systems. Each subsystem itself consist of some other components, which will be discussed later on.

Solar collector and hot water tank and other components are packed and transferred to Europe by container ship and sent to the final installation site.

So the following items are inside the system boundary

- Extraction and process of raw material, and fuel
- System manufacturing and assembling
- Installation

- Operation (electricity for the pump)
- Maintenance, mostly replacing the anti-icing liquid.
- All transports
- Auxiliary heating system (Natural gas and wood pellet)

Two main type of collectors are studied here FPC, ETC, use a metal plate (copper, aluminum or steel) as an absorber, with a coating of black chrome.

In FPC, steel plate absorber and the copper pipes of heat transfer fluid are welded under the absorber plate and enclosed within the steel box and glazing of solar glass. The heat transfer fluid (water glycol) is flow (forced by an electric pump) from the heat pipes to the copper manifold; then with a heat exchanger, the produced heat will transfer to heat tank (Figure 18).

For ETC, the copper heat pipe welded to the copper fines, inside the vacuum-sealed glass tube. The fines are covered by black chrome as well, and the heated fluid inside the copper tube is methanol. The heat pipe is connected to a header which contains the flow of secondary heat transfer fluid (water glycol) to transfer the produced heat to the tank.

For sanitary use, another heat exchanger inside the hot water tank, heat the fresh water to send to end user, and for space heating, either the water glycol inside the hot water tank directly flows in radiator system, or another heat exchanger will have used for space heating circulation network.

Rock wool is the primary insulation material used in both systems. The system is roof-mounted, and the aluminum made structure is used. A 25-liter expansion vessel is used for both collectors, made from low-alloyed steel. Moreover, a 100 W electric pump is installed in the systems for forced water circulation. The annual energy consumption of the pump is calculated 55 kWh. [7]

A 1000 L storage tank, made by stainless steel, and insulated by rock wool.

Transport of the raw material to the factory is assumed 200 km for all raw material, then another 200 km to solar thermal system factory, placed in Shanghai. A container contains the system transported from China to Rotterdam port with a container ship. Moreover, final transport to installation destination by a lorry.

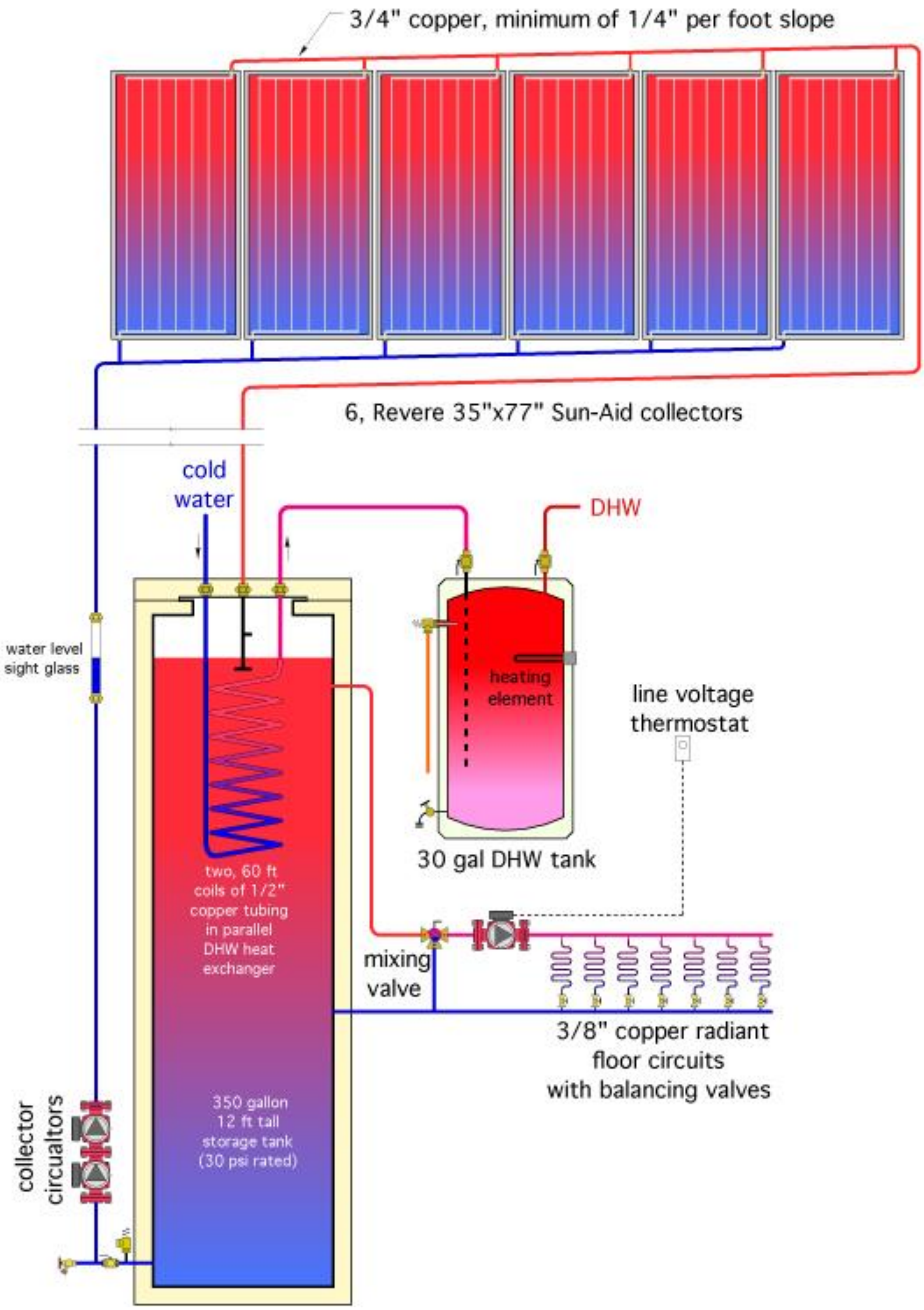

Figure 18 solar thermal combi system configuration [13]

5.5 Life cycle Inventory (LCI)

Life cycle Inventory (LCI) is one of the LCA steps; it involves the collection and quantification of the relevant inputs and output flow for the whole life cycle of the considered production. LCI of a solar thermal system was based on the manufacturing process of each component, bill of used material and manufacturing energy demand. Production process and assembly data collected considering the whole supply chain of the elements and assembled product.

The inventory data of the solar-thermal system has been collected with the following assumptions:

- The data is collected per m² area of the collector, then modified by the design area of the system (for collector elements, and internal piping)
- One storage tanks will be considered, which have 1 m^3 or 1000L capacity

Table 11 Inventory table [7]

Component	Raw material	Flat plate collector	Evacuated collector	Unit
Absorber (per m² gross area)	Copper	2.82	2.8	kg
	Low-alloyed steel	32	20	kg
	Low-iron solar glass	9.12		kg
	Sheet rolling	2.82	2.8	kg
	Selective coating (black chrome) copper sheet	1	1	m²
	glass tube, borosilicate		14.2	kg
	Hydrochloric acid (30% in water)		0.113	kg
	Organic chemicals (methanol)		0.0113	kg
Framework (per m² gross area)	Aluminum	3.93		kg
	Rock wool	2.43	2.03	kg
	Stainless steel	4.14	4	kg
Heat-transfer fluid (per m² gross area)	Propylene glycol	1.01	0.65	kg
Manufacturing energy (per m² gross area)	Electricity (medium voltage):	4.18	61.2	MJ
	Natural gas		16.5	MJ
Pipework (per m² gross area)	Pipework and manifold: copper	8	8	kg
	Pipework insulation: elastomer	4	4	kg
Miscellaneous (per m² gross area)	Corrugated board	3.68	3.33	kg
	Brazing solder (cadmium free)	0.00368	0.1	kg
	Silicone product	0.0588	0.0533	kg
	Soft solder	0.0588	0.0588	kg
	Synthetic rubber	0.732	0.667	kg
	Water	9.4	53.6	kg
	Water, completely softened	1.38	0.9	kg
Pump	Aluminum	0.05	0.05	kg
	Cast iron	3	3	kg

	Copper	0.625	0.625	kg
	Polyvinylchloride	0.075	0.075	kg
	Stainless steel	2.3	2.3	kg
	Synthetic rubber	0.0175	0.0175	kg
Expansion vessel	Alkyd paint	0.07	0.07	kg
	Butyl acrylate	0.7	0.7	kg
	Corrugated board	0.5	0.5	kg
	Low-alloyed steel	4.7	4.7	kg
	Polypropylene	0.025	0.025	kg
	Welding	0.5	0.5	M
	Electricity (medium voltage)	30.996	30.996	MJ
	Light fuel oil =0.5 kg	20	20	MJ
Operation	Electricity	150	150	kWh/year
Maintenance	Propylene glycol	13.1	13.1	kg/25year

Table 12 inventory of hot water tank [14]

	Raw material	Amount	Unit
Hot water Tank 1000 L	Alkyd paint	1.68	kg
	Glass wool	33.36	kg
	Low-alloyed steel	366.96	kg
	Polyvinylchloride	3.32	kg
	Stainless steel	66.72	kg
	Tap water	1029.16	kg
	Welding	12.88	m
	Electricity (medium voltage)	208.36	MJ
	Natural gas LHV 35	255.6	MJ

Table 13 recycling strategy [7]

	Raw material	Recycling strategy
Decommissioning	Aluminum	90% recycled; 10% landfilled
	Copper	41% recycled; 59% landfilled
	Steel	61.7% recycled; 38.3% landfilled
	Plastics	100% landfilled
	Propylene glycol	100% to wastewater treatment
	Glass:	62% recycled; 38% landfilled
	Methanol:	100% to hazardous waste incineration

Table 11 presents the inventory detail of the solar collector assembly, the absorber, the framework, the pump, the expansion valve plus the materials and energy that have been used in the manufacturing process. In the very last column the amount of antifreeze liquid which must replace in 25 years operation is presented. It has to be mentioned that to mentioned that maintenance of the system will be done every six months, which consist of light transport of the personnel, but transports are not mentioned in the table.

Table 17 presents the inventory of a steel water tank with a capacity of 1000Liter, made by steel sheets welded and colored, then insulated with glass wool.

In Table 13 the final disposal strategy of the system after 25 years life cycle is reviewed, which is not involved in the LCA but mentioned here for further researches.

5.6 Life Cycle Impact Assessment (LCIA)

Life Cycle Impact Assessment aims to aggregate the information collected in the LCI phase, to obtain the required damage categories, like Global Warming Potential (GWP), Acidification Potential (AP) and Eutrophication Potential (EP).

The Impact Assessment method which used in this research, to evaluate the environmental impacts, was CML (baseline V4-2015), this method is developed by the Institute of Environmental Sciences, Leiden University, in the Netherlands.

CML is an impact assessment method which restricts quantitative modeling to early stages in the cause-effect chain to limit uncertainties. Results are grouped in midpoint categories according to common mechanisms (e.g., climate change) or commonly accepted groupings (e.g., Acidification). [15]

The LCIA was performed for two types of solar-thermal systems, Flat Plate Collector (FPC) and Evacuated Tube Collector (ETC), with the collector areas of 10-40 square meters. The results are displayed in table 14 and 15.

Table 14 LCA results of flat plate collector versus. area of the collector

FPC **Area m²**	**Unit**	10m²	15m²	20m²	25m²	30m²	35m²	40m²
Climate change - GWP100	kg CO_2 eq.	5701	6929	8158	9387	10616	11845	13074
Acidification potential - average Europe	kg SO_2 eq.	51	70	89	108	127	149	165
Eutrophication – generic	kg PO_4 eq.	32	44	56	68	80	92	103

Table 15 LCA results of Evacuated Tube collector versus. area of the collector

ETC **Area m²**	**Unit**	10m²	15m²	20m²	25m²	30m²	35m²	40m²
Climate change - GWP100	kg CO_2 eq.	5984	6984	7984	8984	9984	10984	11984
Acidification potential - average Europe	kg SO_2 eq.	44	59	74	89	104	119	134
Eutrophication – generic	kg PO_4 eq.	30	39	48	56	65	74	83

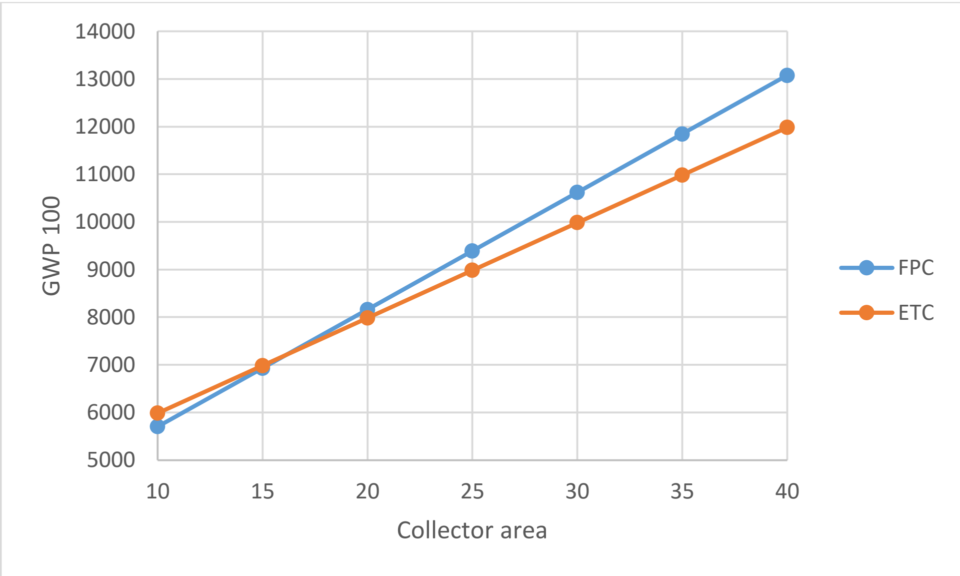

Figure 19 Global Warming potential versus. Collector area in FPC & ETC

For the solar thermal packages, with collector area smaller than 15 square meters, the global warming potential of FPC is slightly less than ETC; as it is shown in Figure 19, for collector area more than 15 square meters, the discrepancy between two collector types rises, up to a point, that in collector area of 40 m², the difference is around 1000 kg CO3eq for a package of solar thermal system. The presented results in Table 14 and Table 15 are the results for a whole system, consist of panels, tank, piping, and support.

5.6.1 GWP of solar thermal systems

The LCA results are per unit of the solar thermal system. With dividing the GWP of the unit system, with the heat generated by the system (dependent on the city and collector area) the LCA of the solar thermal heat generation per unit of heat generated (kWh) is achieved.

5.6.1.1 Single-family house

The LCA results of generated heat by the solar thermal system in a single family house shown in Table 16 and Table 17.

Table 16 GWP of FPC for a single- family house, kg CO_2 Equivalent per kWh heat

FPC Area m²	10 m²	15 m²	20 m²	25 m²	30 m²	35 m²	40 m²
Seville	0.0658	0.0673	0.0708	0.0749	0.0795	0.0845	0.0897
Madrid	0.0618	0.0586	0.0583	0.0594	0.0611	0.0631	0.0653
Rome	0.0750	0.0736	0.0748	0.0771	0.0800	0.0830	0.0865
Milan	0.0873	0.0842	0.0838	0.0846	0.0861	0.0881	0.0904
Bucharest	0.0719	0.0688	0.0685	0.0693	0.0706	0.0723	0.0741
Vienna	0.0921	0.0886	0.0890	0.0903	0.0926	0.0955	0.0986
Paris	0.0987	0.0940	0.0938	0.0953	0.0973	0.0992	0.1024
Prague	0.1108	0.1031	0.1007	0.1006	0.1017	0.1035	0.1057
Berlin	0.1118	0.1079	0.1087	0.1114	0.1142	0.1175	0.1223
Helsinki	0.1207	0.1181	0.1188	0.1215	0.1245	0.1277	0.1309

Table 17 GWP of ETC for a single family house, kg CO_2 Equivalent per kWh heat

ETC Area m²	10 m²	15 m²	20 m²	25 m²	30 m²	35 m²	40 m²
Seville	0.0611	0.0599	0.0605	0.0624	0.0652	0.0688	0.0729
Madrid	0.0538	0.0483	0.0464	0.0465	0.0472	0.0483	0.0497
Rome	0.0644	0.0603	0.0592	0.0597	0.0609	0.0628	0.0650
Milan	0.0706	0.0636	0.0603	0.0588	0.0583	0.0584	0.0591
Bucharest	0.0594	0.0538	0.0512	0.0500	0.0498	0.0502	0.0507
Vienna	0.0743	0.0680	0.0658	0.0649	0.0648	0.0652	0.0660
Paris	0.0772	0.0691	0.0665	0.0659	0.0660	0.0665	0.0673
Prague	0.0875	0.0766	0.0717	0.0696	0.0691	0.0695	0.0703
Berlin	0.0876	0.0793	0.0774	0.0773	0.0781	0.0794	0.0810
Helsinki	0.0960	0.0893	0.0864	0.0854	0.0856	0.0866	0.0881

Figure 20 is the GWP per kWh thermal energy, for a single family house in Paris for instance, for the system with FPC, meets the minimum emission in collector area of around 20m², for the ETC the minimum happens in 25m².

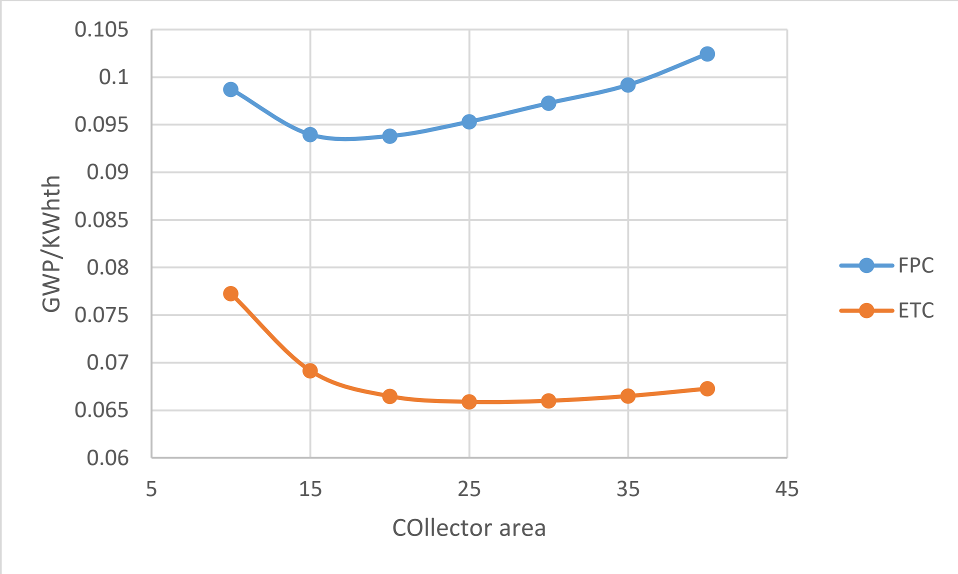

Figure 20 GPW per kWh delivered thermal energy in a single family house, for Paris, CO_2 Eq. Per kWh.

The same trend can also be seen in other cities, but the difference is more significant in cities with the colder climatic condition. So, in general, using the vacuum tube collector produces less global warming potential.

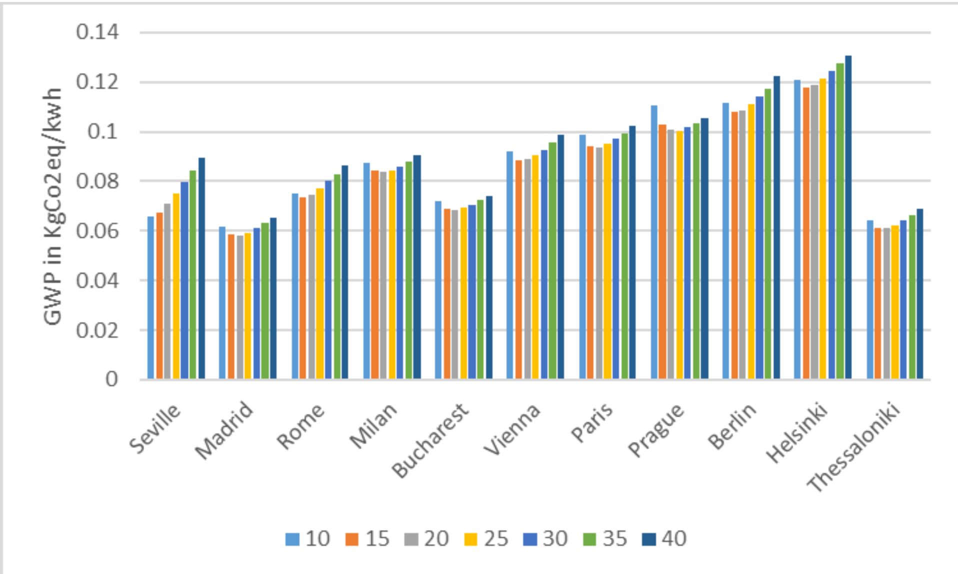

Figure 21 Flat plate collector global warming potential per kWh generated for a single family house

The global warming potential in different cities concerning collector area for FPC, shown in Figure 21 (except Seville) follows the same trend as collector area. For the rest of the cities, the lowest emission production has been found for collector areas of around 15-20 square meters. On the other hand, for the evacuated tube collector, the behavior is different between studied cities; for instance, in Seville, with increasing the collector area, the emission increases, but in Bucharest, and Prague this trend is the opposite, and in the other cities it follows the parabolic trend with the vertex of 15-30 square meters (Figure 22).

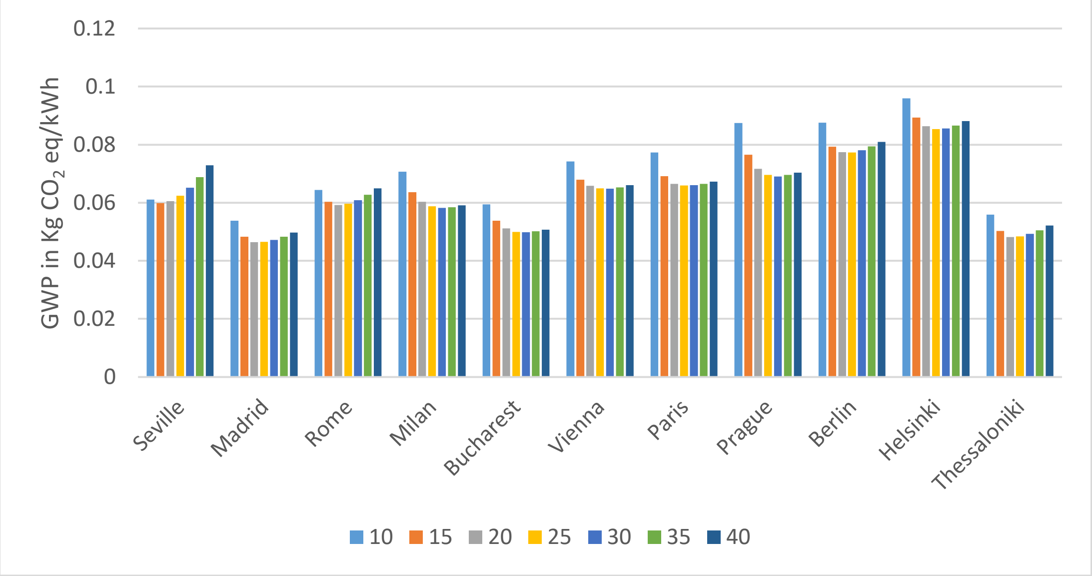

Figure 22 Evacuated tube collector Global warming potential per kWh generated heat for a single family house

In Mediterranean region environmental gain of using the ETC instead of FPC is much smaller then northern parts of Europe, for example in Helsinki, the average gain of this replacement is 0.025-0.043 kg CO_2/kWh; we need to consider that, less emission is not just because of solar-thermal system manufacturing processes, but it's also because of producing more heat by the ETC system during cold seasons, which in the case of Helsinki, it will be 4-5 percent more coverage of heating demand. More coverage by solar system means less demand for auxiliary heating (Electric or Gas or Diesel) and reduction of fuel consumption and less emission in this view as well. This comparison will be discussed later.

5.6.1.2 Apartment block

The same procedure is established for calculating the GWP of using the solar thermal system to cover the heat demand of an apartment block.

Table 18 GWP of FPC for apartment block, kg CO_2 Equivalent per kWh heat

FPC Area m²	10 m²	15 m²	20 m²	25 m²	30 m²	35 m²	40 m²
Seville	0.0278	0.0241	0.0227	0.0223	0.0224	0.0230	0.0239
Madrid	0.0326	0.0278	0.0258	0.0250	0.0247	0.0248	0.0253
Rome	0.0368	0.0314	0.0292	0.0283	0.0281	0.0283	0.0287
Milan	0.0451	0.0383	0.0354	0.0342	0.0337	0.0338	0.0341
Bucharest	0.0395	0.0332	0.0304	0.0291	0.0284	0.0282	0.0282
Vienna	0.0531	0.0443	0.0402	0.0381	0.0369	0.0363	0.0360
Paris	0.0595	0.0499	0.0455	0.0433	0.0422	0.0417	0.0416
Prague	0.0703	0.0585	0.0530	0.0500	0.0484	0.0475	0.0470
Berlin	0.0650	0.0540	0.0489	0.0461	0.0446	0.0437	0.0432
Helsinki	0.0674	0.0561	0.0509	0.0482	0.0466	0.0458	0.0455

Table 19 GWP of ETC for apartment block, kg CO_2 Equivalent per kWh heat

ETC Area m²	10 m²	15 m²	20 m²	25 m²	30 m²	35 m²	40 m²
Seville	0.0249	0.0207	0.0189	0.0183	0.0185	0.0190	0.0195
Madrid	0.0284	0.0232	0.0209	0.0197	0.0194	0.0195	0.0197
Rome	0.0316	0.0259	0.0233	0.0220	0.0215	0.0216	0.0220
Milan	0.0371	0.0302	0.0270	0.0254	0.0246	0.0243	0.0245
Bucharest	0.0331	0.0267	0.0237	0.0221	0.0211	0.0206	0.0204
Vienna	0.0435	0.0347	0.0306	0.0282	0.0269	0.0260	0.0255
Paris	0.0474	0.0380	0.0336	0.0312	0.0298	0.0290	0.0285
Prague	0.0554	0.0442	0.0388	0.0358	0.0340	0.0329	0.0322
Berlin	0.0515	0.0410	0.0360	0.0331	0.0314	0.0303	0.0296
Helsinki	0.0537	0.0429	0.0377	0.0348	0.0331	0.0320	0.0314

In general, the coverage of the solar thermal system in an apartment block is much less than a single family house, due to more DHW demand because of more people living in the block in compare to single-family house (50 m² per person in single-family house and 25 m² per person in apartment block) and much more significant area need to be heated (140 m² in single-family house versus 990 m² in apartment block)(Table 18,20).

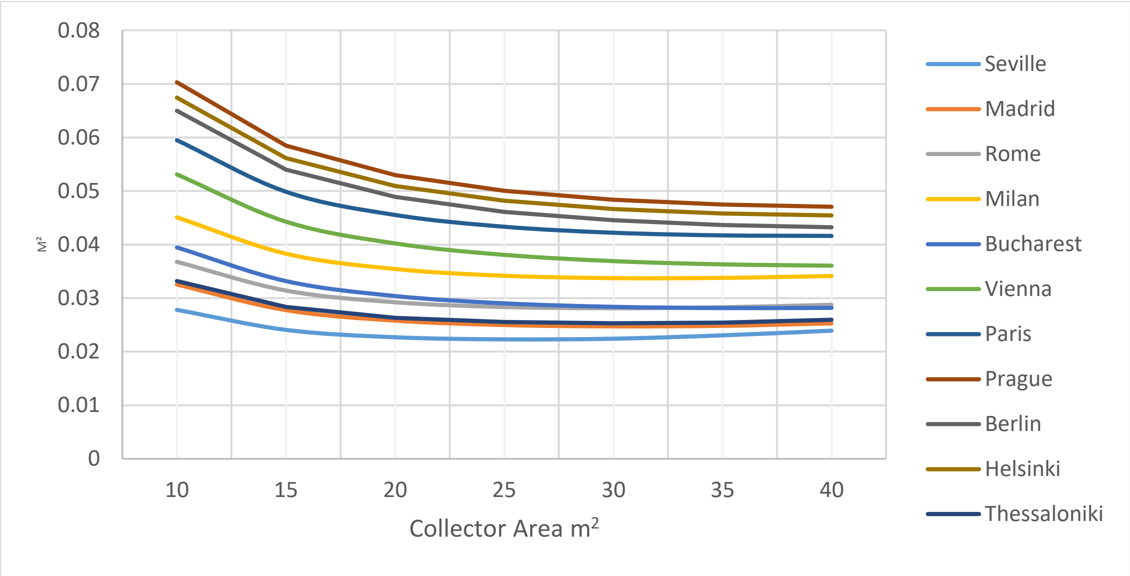

Figure 23 GWP (kg CO_2 eq. per kWh) versus FPC collector area, for an apartment block

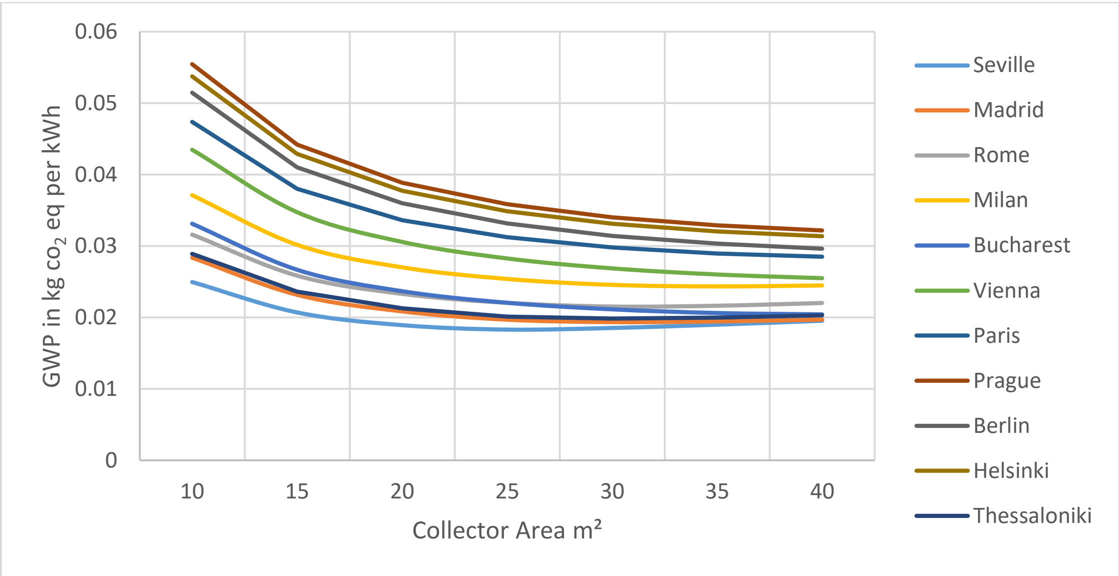

Figure 24 GWP (kg CO_2 eq. per kWh) versus ETC collector area, for an apartment block

As shown in Figure 23 and Figure 24, the global warming potential of using the solar thermal system to cover the heating demand of an apartment block is decreased as we increase the area of the collectors.

There is just one exception in this trend, the city of Seville, which the minimum GWP is met in the collector area of 25-30 m², in result of covering the demand in this collector area, and more collector area just incerase the emission whitout added usable energy production.

5.6.1.3 Free solar thermal system

Another approach to calculating the solar thermal system emission calculation can be examining the heat production of the system, regardless of the demand and usability of the produced heat. It is the method mostly used in previous literature. To evaluate the result, this LCA calculation is also performed.

To calculate the LCA, regardless of the demand, we need to assume a fixed demand, far from the range of the solar thermal system that never meets un-used energy.

Table 20 GWP of FPC regardless of demand, kg CO_2 Equivalent per kWh heat

FPC Area m²	10	15	20	25	30	35	40
Seville	0.0262	0.0220	0.0202	0.0193	0.0188	0.0187	0.0188
Madrid	0.0313	0.0262	0.0240	0.0228	0.0222	0.0220	0.0220
Rome	0.0352	0.0294	0.0268	0.0254	0.0247	0.0244	0.0243
Milan	0.0434	0.0362	0.0330	0.0312	0.0303	0.0299	0.0297
Bucharest	0.0389	0.0325	0.0296	0.0282	0.0274	0.0270	0.0269
Vienna	0.0530	0.0441	0.0401	0.0379	0.0367	0.0361	0.0359
Paris	0.0584	0.0486	0.0440	0.0416	0.0402	0.0394	0.0391
Prague	0.0699	0.0580	0.0524	0.0494	0.0476	0.0467	0.0461
Berlin	0.0649	0.0539	0.0488	0.0461	0.0445	0.0436	0.0432
Helsinki	0.0672	0.0558	0.0506	0.0478	0.0462	0.0454	0.0450

Table 21 GWP of ETC regardless of demand, kg CO_2 Equivalent per kWh heat

ETC Area m²	10	15	20	25	30	35	40
Seville	0.0239	0.0193	0.0171	0.0160	0.0154	0.0151	0.0149
Madrid	0.0274	0.0220	0.0195	0.0182	0.0174	0.0170	0.0168
Rome	0.0304	0.0244	0.0215	0.0200	0.0191	0.0186	0.0183
Milan	0.0360	0.0289	0.0255	0.0236	0.0225	0.0219	0.0215
Bucharest	0.0328	0.0263	0.0233	0.0216	0.0207	0.0201	0.0198
Vienna	0.0435	0.0347	0.0306	0.0283	0.0269	0.0261	0.0256
Paris	0.0468	0.0373	0.0328	0.0303	0.0288	0.0278	0.0273
Prague	0.0553	0.0441	0.0387	0.0357	0.0338	0.0327	0.0320
Berlin	0.0516	0.0412	0.0362	0.0334	0.0317	0.0307	0.0300
Helsinki	0.0538	0.0429	0.0378	0.0349	0.0332	0.0321	0.0315

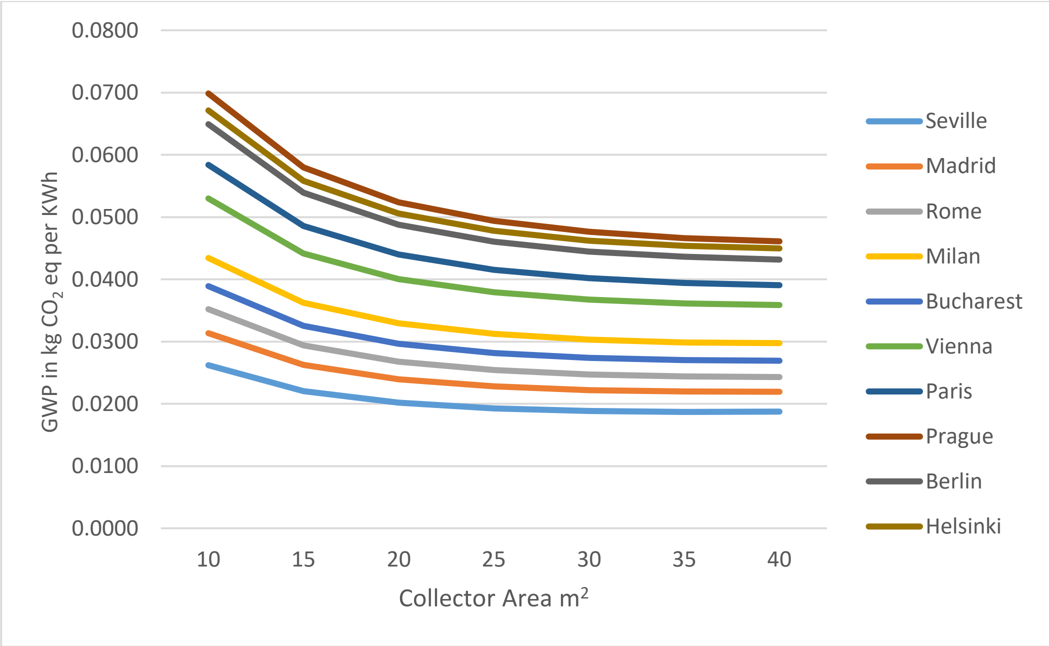

Figure 25 GWP of FPC regardless of demand

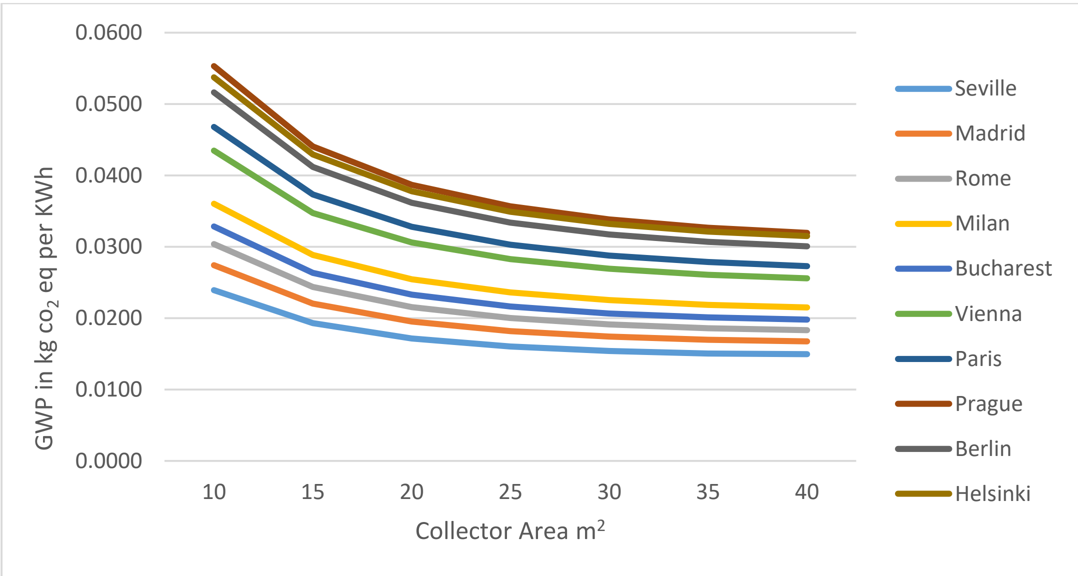

Figure 26 GWP of ETC regardless of demand

Figure 25 and Figure 26 show the GWP of FPC and, ETC in studied cities, with collector areas from 10 to 40 m². The results show that with increasing the collector area, GWP per kWh of thermal energy decreases. This amount can be as low as 20 gram per kWh, in the Mediterranean region.

5.7 Acidification and Eutrophication potential

Acidification potential (AP) and Eutrophication potential (EP) will follow the same route as the GWP. Figure 27shows the AP/kWh, Figure 28 and Figure 29 shows the effect of increasing collector area on AP and EP, for both types of collectors.

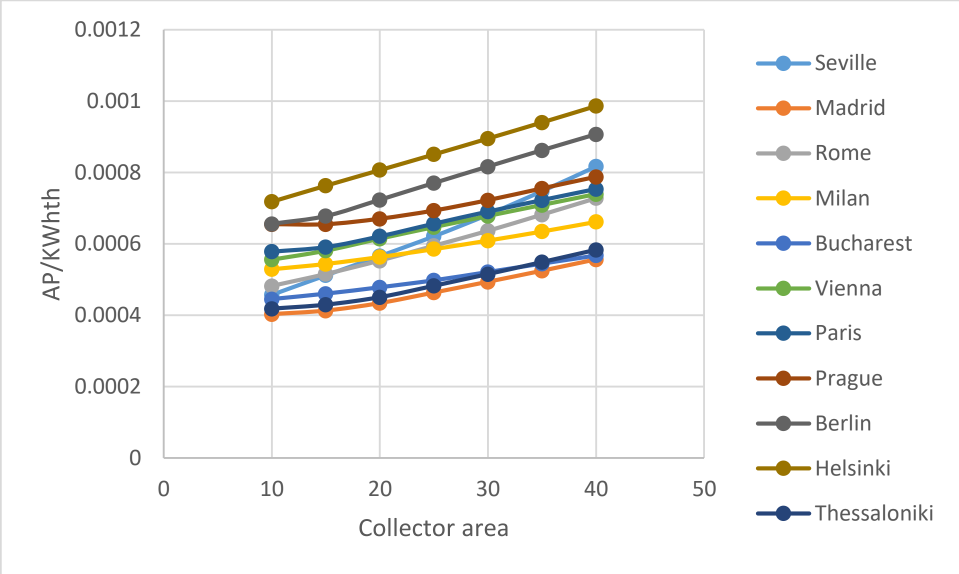

Figure 27 AP for a single family house, SO_2 eq. per kWh thermal energy, vacuum tube collector

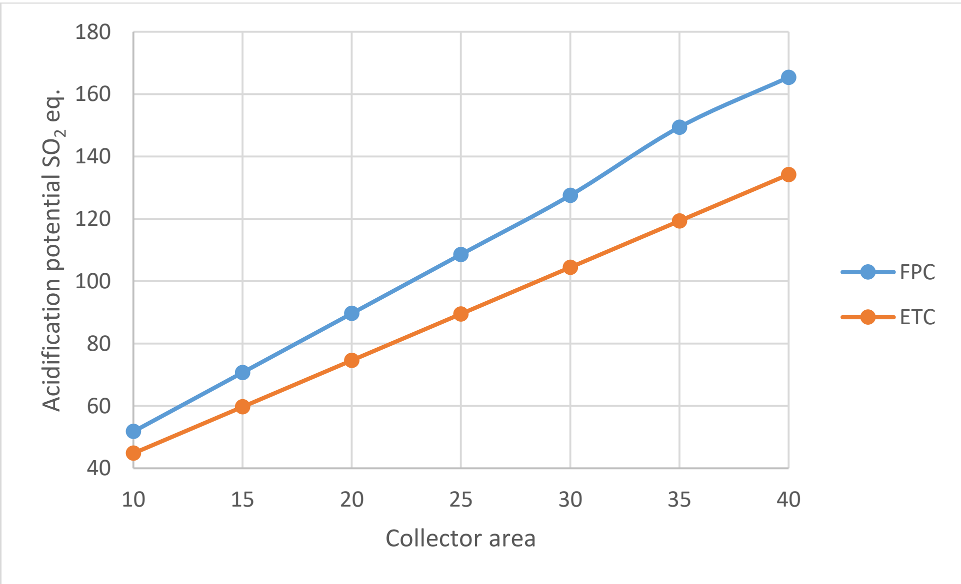

Figure 28 Acidification potential for single family house

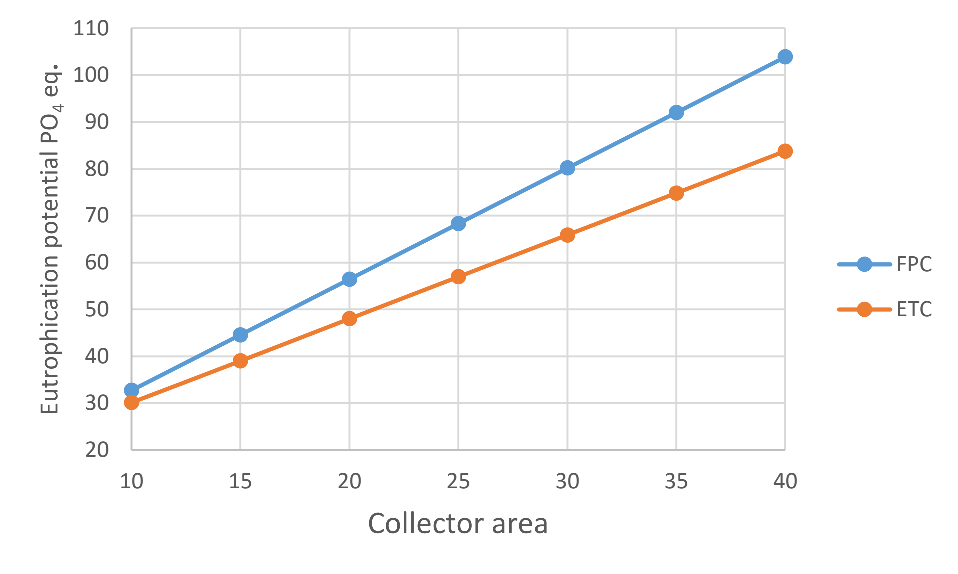

Figure 29 Eutrophication potential for single family house

In average, the AP of using the solar thermal system in Europe is between 0.4-1 gr of SO_2 eq. Per kWh of heat produced by the solar thermal system, with vacuum tube collectors.

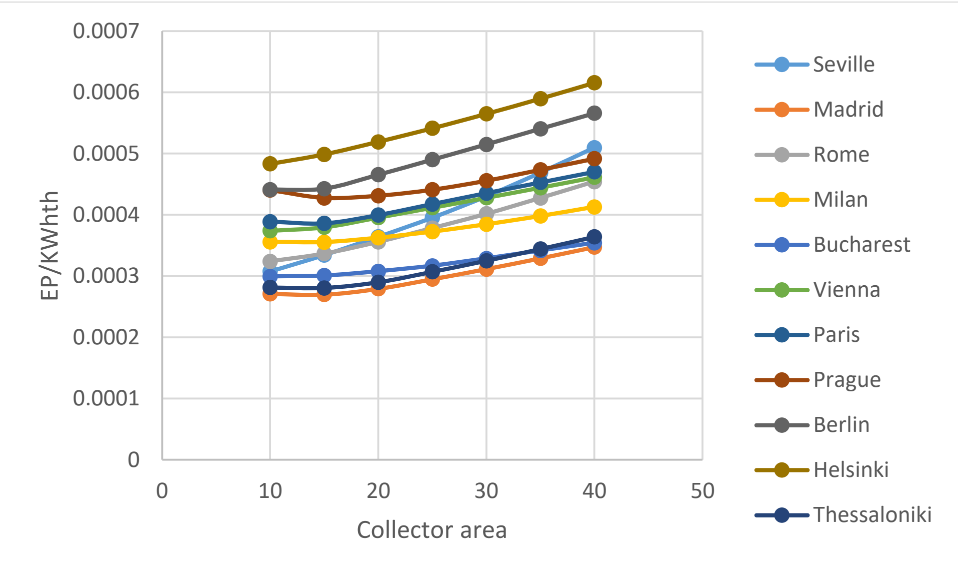

Figure 30 EP for a single family house, PO_4 eq. per kWh thermal energy, vacuum tube collector

The same trend is observed for EP, the Eutrophication potential per kWh thermal energy produced by the collector, for a single family house in different cities is presented in Figure 30.

The average EP of using solar thermal system equipped with vacuum tube collectors, in a single-family house is 0.3-0.6 gr of PO_4 eq — per kWh of produced thermal energy.

5.8 Interpretation of LCA results

We did the LCA analysis of a solar thermal system, with two different technologies, flat plate collector, and evacuated tube collector, for two different buildings, single-family house, and apartment block, in 11 big cities, in different climatic conditions around Europe.

The results for a single-family house, was mostly parabolic, like Figure 22, it means that there is a minimum emission point, somewhere in the middle of the studied range of collector area, but for the apartment block, as much as we increased the solar thermal collector area, the GWP decreased.

This is because of unused heat produced during hot season with the solar thermal system, in the case of single family house, because the hot water demand in summer is much less than of an apartment block, in summer we have much extra heat, which because of no need for space heating in summer, is useless.

Figure 31 shows the schematic comparison of the discussed phenomenon, the solar potential is in its maximum power in summer, when we do not need heating energy. On the other hand, because of the higher demand of the apartment block, we can use almost all the power produced by the system, so as much as we increase the surface area of the collector, we use all the produced heat, then it decreases the GWP per kWh, because of more kWh.

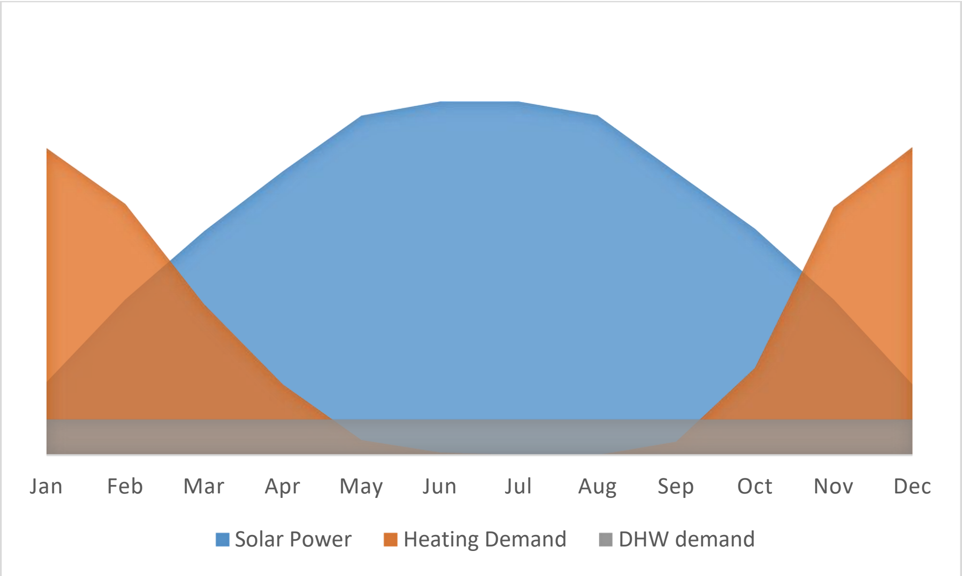

Figure 31 Schematic of a monthly comparison of solar radiation and heating demand

Because of high solar irradiation potential of Seville, in collector areas more than 30 m^2 we will cover 100% of the DHW demand, and extra heat will be wasted. Because of this, in this city, we will see a return in GWP in high collector areas.

There are some ways to store the heat produced in summer to use in winter, which is known as seasonal energy storage systems. However, this was not discussed in this study.

6 Auxiliary heat

As we discussed previously, a specific percentage of heat demand regarding the location and area of the collector, is covered by the solar thermal system. The rest of this heating demand must be covered with another source of energy, natural gas, oil, and wood pellet, will deliberate in this chapter. Moreover, the fuels have provisions like extraction, preparation, and transport.

Tables below (Table 22,Table 23) show the heating energy which is not covered by the solar thermal system and need to be produced by the auxiliary system.

Table 22 Auxiliary heat demand of FPC, MJ

AUX HEAT (MJ)	10	15	20	25	30	35	40
Seville	13229.5	10887.1	9110.6	7659.0	6479.2	5518.0	4722.3
Madrid	46646.4	42907.9	39782.7	37149.4	34886.8	32873.8	31085.3
Rome	30475.7	27861.1	25718.7	23896.0	22316.7	20866.0	19656.9
Milan	79497.0	77053.8	74882.8	72923.4	71151.5	69543.3	68074.8
Bucharest	91695.9	88619.3	85961.1	83600.9	81464.8	79518.4	77727.3
Vienna	99462.5	97116.7	95167.0	93410.0	91862.6	90518.3	89283.4
Paris	88150.0	85844.8	83940.9	82282.4	80747.7	79267.1	78088.2
Prague	121059.2	118792.6	116799	115027.6	113438.9	111993.2	110650.7
Berlin	85494.0	83587.3	82030.9	80696.4	79455.6	78323.9	77437.6
Helsinki	84925.8	83275.8	81840.1	80597.2	79446.8	78370.6	77350.4
Thessaloniki	47194.0	43666.0	40723.6	38256.4	36154.0	34306.2	32614.4

Table 23 Auxiliary heat demand of ETC, MJ

AUX HEAT (MJ)	10	15	20	25	30	35	40
Seville	11591.8	8905.2	6714.5	4958.2	3651.0	2726.2	2043.5
Madrid	43916.0	39104.5	35168.2	32112.4	29464.8	27170.1	25186.6
Rome	28039.0	24746.1	22000.3	19752.4	17804.2	16231.9	14877.7
Milan	76708.2	73097.9	69832.9	66885.6	64228.1	61833.0	59693.3
Bucharest	88620.9	84439.7	80654.7	77226.1	74265.1	71584.0	69068.8
Vienna	96771.5	93580.2	90897.8	88452.2	86201.6	84131.8	82228.5
Paris	85310.1	81921.8	79170.2	76830.1	74681.7	72679.1	70813.7
Prague	118617.4	115336.9	112437.1	109872.2	107649.5	105718.9	103934
Berlin	83001.5	80150.7	77984.3	76103.4	74418.2	72907.4	71522.8
Helsinki	82747.5	80464.2	78414.5	76577.5	74932.1	73457.4	72132.2
Thessaloniki	44497.5	39905.5	36073.3	33204.0	30739.0	28627.9	26800.3

Table 24 Selected fuel-related CO_2 emission factors [18]

Fuel	HHV measured (kJ/kg)	CO_2 (kg CO_2/GJ)
Natural Gas	55,500	56
petrol	51,100	73.1
Diesel ($C_{12}H_{23}$)	45,000	74
Coal (Anthracite)		97.6
Wood	17,100	109.6
Oil	38,200	

Natural gas is the dominant player in the heating market of Europe, mostly supplied by Russia and Norway. The other big energy carrier of heating in Europe is oil and biomass. Main used biomasses for heating are wood and woodchips. Later in this chapter, we will discuss the efficiency of heat production with these energy conversion systems.

6.1 Natural gas heater

Natural Gas, with more than 37% is still the most used energy carrier in EU 27 countries. Russian natural gas pipeline made this country the biggest supplier of energy for EU, followed by Norway. [1]

Natural gas is often called as a clean energy alternative. It burns more cleanly than other fossil fuels, emitting lower levels of harmful emissions such as carbon monoxide, carbon dioxide, and nitrous oxides. It produces fewer greenhouse gases than other fossil fuels do. [16]

Rather than the natural gas burning emissions, there are emission and energy consumptions regarding the extraction and transport of the fuel Gas, with the pipeline, (assumed 4000km from Russia) which is calculated as 12.7 g CO_2 eq., per MJ of natural gas, and 0.14 MJ energy per MJ of natural gas. [17]

Moreover, even though natural gas is a clean fuel, and with the assumption of complete combustion in an advanced and high-performance furnace, 56 kg of CO_2 produced with burning one GJ of natural gas (see Table 24).

With all these considerations, the emission per kWh of heating production by natural gas water heater furnace, calculated.

Table 25 LCI of the Natural gas furnace [19]

Material	KG
Aluminum	1.02
Brass	0.05
Ceramic	0.04
Circuit board, transistors	0.05
Copper	2.2
Fiberglass insulation (foil-lined)	0.27
Galvanized Steel	21.86
PET	0.38
PVC	0.45
Powder coating	0.19
Rubber	0.02
Steel	29.79
Total	56.3

The selected Natural gas furnace is 13 KW Rheem Classic, RGRC-04, with the efficiency of 95%.

Overly, using a natural gas heating system, for hot water and heating of the residential building, with a high-performance furnace, will produce 250-272 gram CO_2 equivalent per kW of heat.

6.2 Oil heater

Several kinds of oil produced in the petroleum industry, but only one is widely used for most home heating. Fuel oil Number 2, which delivers 38.2 MJ of potential heat energy per liter is the most popular in the residential sector. The mid-efficiency oil furnaces for space heating (hot water radiators) and domestic hot water, which not equipped with oil condenser, have the efficiency of 60-87 percent [20]

The fuel oil furnace for residential use is studied in a report in 2013 by Lal Mahalle. The amount of GWP of district heating and hot water in a residential building is calculated as 92.62 kg CO_2 eq per GJ of heat (Mahalle, 2013) which equals to 333-gram CO_2 eq. Per kWh of heat. Need to note that the studied system is a non-condensing furnace. [19]

6.3 Pellet

6.3.1 Pellet production overview

The feedstock of pellet production is wood fiber (wood chips) and sawdust (straw pellets are mostly used in industrial facilities because of higher ash content). The feedstock then guided to chippers and hammer mill to convert to small particles. One of the pellet quality factors is the level of moisture, so drying the feedstock before sending to the extrusion process is vital. In the extrusion phase, the biomass is pushed through the mesh under high pressure and temperature, where the particles will stick together to turn into the pellet. The produced pellets then cooled and dried before packing into bags.

6.3.2 LCI of Pellet

The input LCI of the pellet production is energy and fuel and bio-mass. However, with the cradle to grave perspective, we need to consider that the pellet is the biomass residues which capture CO_2 during their life period, which as a sequestered CO_2 in the process, reduce the overall CO_2 emission of pellet use.

There is a considerable difference between the literature for global warming potential and in general environmental effect of using pellet for heating. In 2010, Caserini claimed that global warming potential of using pellet is just the result of harvesting, transport, and manufacture of the pellets because the CO_2 released during the combustion phase is equal to the amount of CO_2 captures by the tree. He calculates the climate change impact of using pellets between 15-28 gCO_2/MJ heat (54-101 gCO_2/kWh). (Stefano Caserini, 2011) on the other hand, Mahelle in 2013, calculate this difference around two times less than natural gas heater equal to 32 gCO_2/MJ. [19][21]

As far as global warming is concerned, the pellet combustion is the dominant phase of its life cycle, with 82% of global warming impact production. Which is around 127 kg of CO_2 equivalent greenhouse gasses per GJ of heat (457 gCO_2 eq. per kWh). However, 95 kg of this greenhouse gas emissions on CO_2 equivalent basis come from atmospheric carbon captured in pellet during the plant growth. So the net CO_2 produced is as low as 32 kg of CO_2 equivalent per GJ of heat (115 gCO_2 eq. per kWh). On the other hand, the manufacture of the pellet needs is the dominant energy consumer of the overall pellet life cycle (71%) [19][21]

6.4 Conclusion

As discussed in this chapter, different heat sources can be used to cover the AUX hear demand of heating and domestic hot water; we have discussed the three primary sources in EU, Natural gas, Fuel oil, and wood pellet. The cleanest fuel regarding global warming emissions is wood pellet, but we need to keep in mind that pellet also has higher ash content in the exhaust gas, which produces other pollutions (Table 26).

Table 26 Global warming potential of auxiliary energy sources

Impact category	Unit	Pellet	NG	Fuel oil
Global Warming	g CO_2 eq. per kWh	115	250-277	333
Total Energy	MJ per GJ delivered energy	1741.0	1244.5	1375.5

6.5 Heat transfer system

For covering the heat demand of the single-family house, a radiator system will be used, with hot water circulation. 5 Aluminum radiators and required pipes (polypropylene pipe) are calculated, and finally, the LCA analysis of the system according to the designed system is established, the total amount of 609 kg of CO_2 will be produced for production of the heat transfer system. This amount has consumed the energy of the manufacture, transport, installation and maintenance for 25 years.

7 Energy and environment balance

Previously we calculate the solar thermal system environmental emission, and alternative systems emission as well, like a natural gas burner. Here we introduce some indicators to evaluate the performance of the solar thermal heat generation system in comparison to alternative systems.

7.1 Energy Payback period

The first indicator is energy payback time (EPT) defined as the period to produce the equivalent renewable energy (heat) that have been used for construction and assembling as fossil energy

$$E_{PT} = \frac{LCA_{Energy}}{E_{useful} - E_{use}}$$

LCA_{Energy} is the LCA result of fossil energy consumed during manufacturing, consisting of extraction of raw material, manufacturing, assembling and all transports up to install the system. U_{useful} is the useful energy produced per year by the solar thermal system; this factor is what makes the difference between cities and systems. Moreover, E_{use} is the energy used by the system to operate.

For a system with $25m^2$ of collector area, the LCA energy (non-renewable) is 133025 MJ for FPC and 126517 MJ for ETC.

E_{use} is 150 kWh per year, for the operation of the pumps. E_{useful} is depended on the location and demand,

Table 27 Energy payback time for a solar thermal system with 25m² collector

Years	*single family house*		*Apartment block*	
	FPC	ETC	FPC	ETC
Seville	7.1	5.9	2.1	1.7
Madrid	5.7	4.4	2.4	1.9
Rome	7.3	5.6	2.7	2.1
Milan	8.0	5.6	3.3	2.4
Bucharest	6.6	4.7	2.8	2.1
Vienna	8.5	6.1	3.6	2.7
Paris	9.0	6.2	4.1	3.0
Prague	9.5	6.6	4.8	3.4
Berlin	10.4	7.3	4.4	3.2
Helsinki	11.4	8.0	4.6	3.3
Thessaloniki	5.9	4.6	2.4	1.9

In a single family house, with FPC system of 25 m^2 collector area, the energy payback time is 6-11 years, same building with the ETC system meet the energy payback period of 4-8 years (Table 27).

As it was discussed before, due to energy cut in summer in single-family house, the useful energy is limited, so the energy payback time is higher, but for the apartment block, because of higher demand, especially in summer because of higher number of people live in an apartment block, the energy payback time is between 2.2-4.8 year in FPC and 1.7 to 3.4 years for ETC with $25m^2$ of collector area.

7.2 Emission payback period

The other key indicator is emission payback period, which defined as the period emission released by the manufacturing processes of the system are equal to emission avoided due to the employment of the solar thermal system.

This indicator can be calculated for all emission groups like GWP or Acidification. The avoided emission is calculated by the assumption of using the natural gas system as a reference. We have calculated the emissions per energy unit, for the natural gas burner, 250 g CO_2 per kWh of thermal energy. In the case of a solar thermal system, it depends on the end user.

Table 28 GWP payback period for a solar thermal system by years, with 25m² collector

Years	single family house		Apartment block	
	FPC	ETC	FPC	ETC
Seville	10.7	8.3	2.4	1.9
Madrid	7.7	5.7	2.7	2.1
Rome	11.1	7.8	3.1	2.4
Milan	12.7	7.6	3.9	2.8
Bucharest	9.5	6.2	3.2	2.4
Vienna	14.1	8.7	4.4	3.1
Paris	15.4	8.9	5.2	3.5
Prague	16.8	9.6	6.2	4.1
Berlin	20.0	11.1	5.6	3.8
Helsinki	23.6	12.9	5.9	4.0
Thessaloniki	8.3	6.0	2.8	2.1

For the emission group of Global Warming Potential (GWP), the emission payback period is expressing meaningful results. For single-family house, and a solar thermal system with 25m^2 of collector area, the emission payback period is from 7.7 years in Madrid, us to 23 years in Helsinki, it means that the emission produced during manufacturing of the system is almost equal to the avoided emission during 25 years' age of the system in Helsinki. So with environmentally decision rules, it not environmentally friendly to use this FPC solar thermal system in a single-family house. In the case of ETC, the emission payback period is 5.7-13 years (Table 28).

In the case of an apartment block, this payback period is much more acceptable, 2.4-6.2 years for FPC and 2-4 years in the case of ETC system implementation.

To check the effect of solar thermal system area, on the payback period, the same process is performed for 10m2 and 40m2 in the single-family house again; the results show that this emission payback period, influenced a little by the size of the system (Table 29).

Table 29 GWP payback period for a solar thermal system by years, with 10, 25 and 40 m^2, collector area for single family house

Years	10 m^2		25m^2		40m^2	
	FPC	ETC	FPC	ETC	FPC	ETC
Seville	*8.9*	*8.0*	*10.7*	*8.3*	*12.1*	9.6
Madrid	*8.2*	6.8	*7.7*	5.7	*8.6*	6.3
Rome	*10.7*	8.6	*11.1*	7.8	*12.3*	8.7
Milan	*13.4*	9.8	*12.7*	7.6	*13.8*	8.2
Bucharest	*10.0*	7.8	*9.5*	6.2	*10.4*	6.6
Vienna	*14.5*	10.5	*14.1*	8.7	*15.6*	9.3
Paris	*16.3*	11.1	*15.4*	8.9	*16.9*	9.7
Prague	*19.8*	13.4	*16.8*	9.6	*18.9*	10.8
Berlin	*20.2*	13.4	*20.0*	11.1	*22.1*	12.4
Helsinki	*23.3*	15.5	*23.6*	12.9	*25.3*	14.2
Thessaloniki	*8.6*	7.1	*8.3*	6.0	*9.2*	6.7
Average	*14.0*	10.2	*13.6*	8.4	*15.0*	9.3

So with approximation, we can say that the emission payback period of the solar thermal system is independent of the size of the system. Moreover, the emission payback period in the 25m^2 system can be an excellent estimation of the overall system emission payback period regardless of the system size.

7.3 Sensitivity analysis

The sensitivity analysis determines the effect of a change in the value of an independent variable, on the dependent variable. For instance, the leading independent variable in our study is the solar thermal collector area, and we can see the effect of increase or decrease of the area on emission groups like GWP and Acidification in Figure 32. With increasing the collector area, from 25 m^2 to 40 m^2, with the assumption of other variables like tank volume stays constant, the GWP of the system increase 26%.

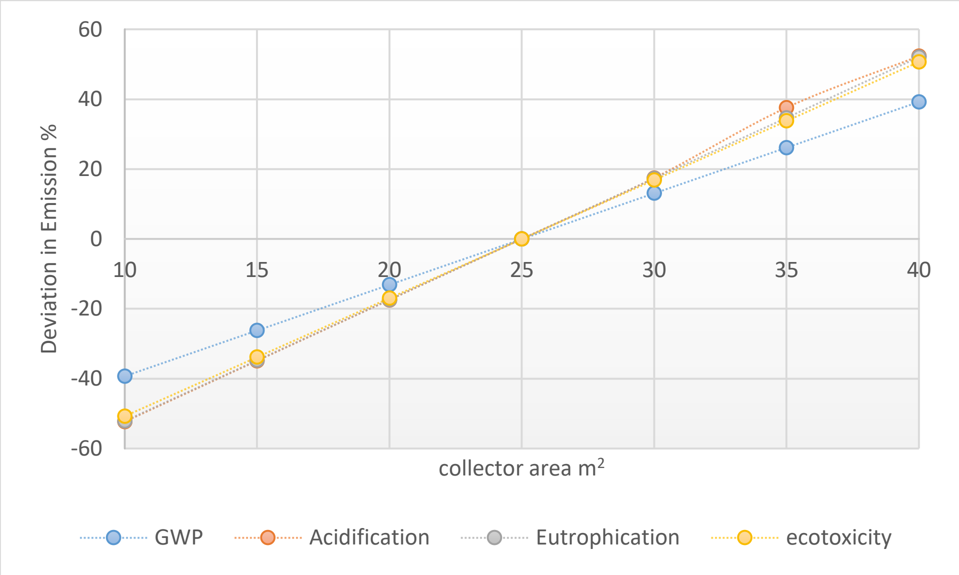

Figure 32 sensitivity analysis of emission deviation by collector area

As it was shown in LCA chapter, the most of emission share in different emission groups is because of steel, copper, and glycol. In GWP, transport has a significant share as well. Here we will perform a sensitivity analysis of this elements.

7.4 Sensitivity analysis of steel use

The very first element we are going to study the effect on emission production in a solar thermal system is steel. As it was shown in LCA results, 35% of GWP in FPC manufacture and 22% in ETC is due to steel. The hot water tank is the central part which is used more than 90% of steel in the solar thermal system (regardless of building piping of DHW and heating circuit, and radiators). It is possible to replace some of this steel with other elements, for example, the composite material can be a replacement for the hot water tank shell.

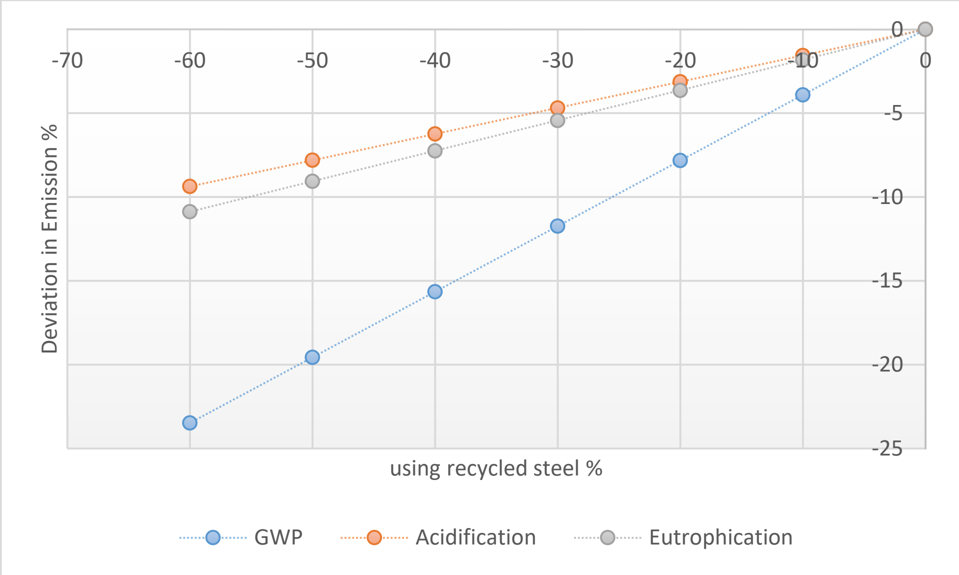

Figure 33 sensitivity analysis of steel usage in FPC

Figure 33 shows the effect of reduction in the use of steel in the solar thermal system (or use the recycled steel) on emission groups for an FPC system. The reduction in the use of steel has an intermediate effect on acidification and eutrophication, but GWP takes a substantial reduction, around 20% with replacing 50% of steel with recycled steel.

7.5 Sensitivity analysis of using propylene glycol

Propylene glycol is an additive, as anti-freeze, anti-boil, and anti-corrosion. The share of the glycol-water mixture is usually defined by the manufacturer. However, because of the severe environmental effect of using this chemical, it is always needed to use it as less as possible. The graphs show the temperature range of working with a specific percentage of glycol in water, so the suitable parentage must use in specific climatic conditions.

The sensitivity analysis of using glycol in Figure 34 shows that, with reduction of using glycol in the heat transfer fluid in an FPC (the same for ETC) system for 50 percent, acidification, eutrophication, and GWP reduced 4.7, 4.2 and 11.2 percent respectively.

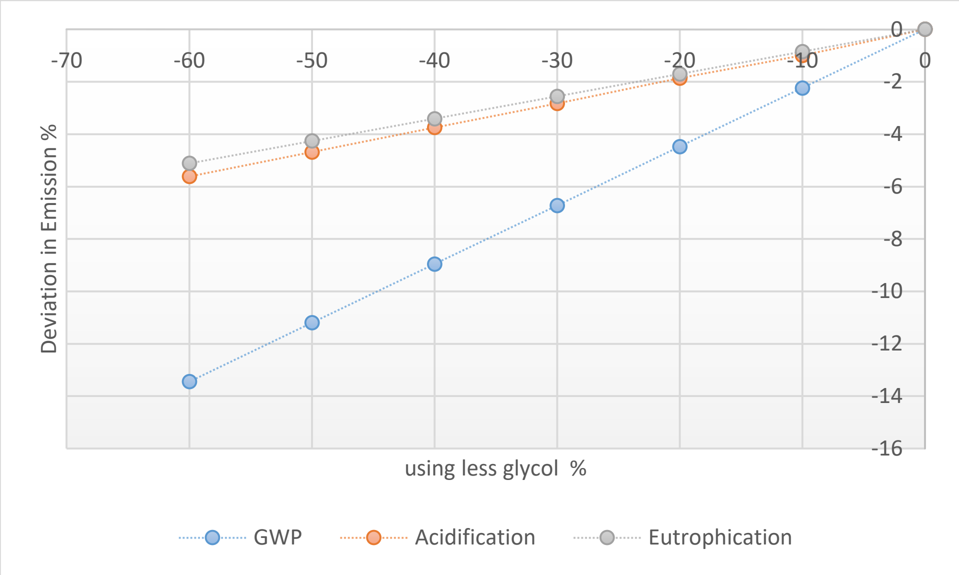

Figure 34 Sensitivity analysis of Glycol use in solar thermal collector

7.6 Sensitivity analysis of copper

The high conductivity of copper makes it the most suitable element to use as a conductor of heat and electricity. However, unfortunately, extraction and production of copper is very pollutant. On the other hand, copper is recyclable, without losing its quality. In volume, copper is the third recyclable metal, after Iron and Aluminum. With recycling the 50% of the copper in the solar thermal system, acidification potential drops by 25% and eutrophication reduces by 31%.

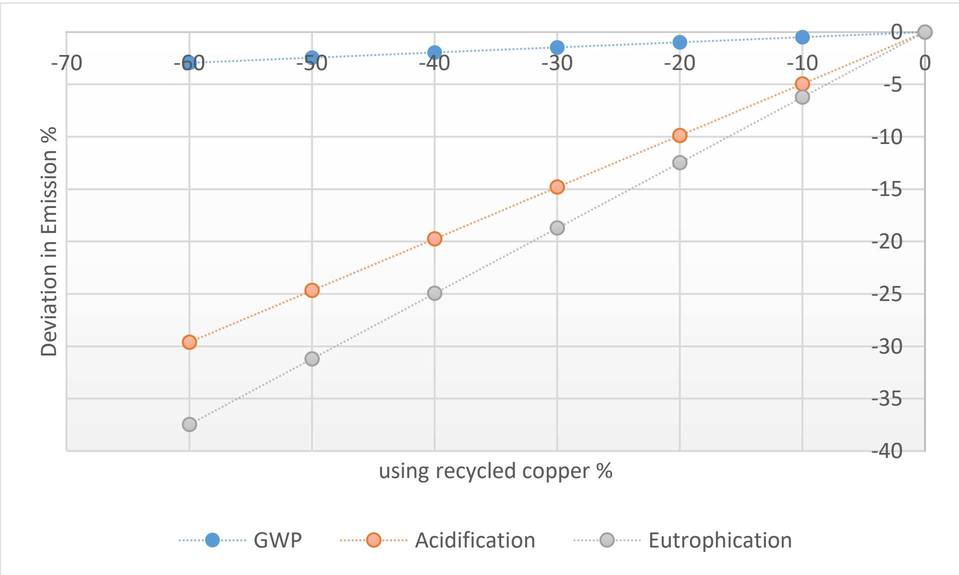

Figure 35 sensitivity analysis of using copper in FPC

7.7 Sensitivity analysis of transportation

The market share of the solar thermal systems shows that chines products dominate most of EU solar thermal market (and in general the world market). Without considering the quality and performance of the products, just with reduce the transport of the raw material and final product by 50%, the GWP of the product reduces more than 3%, and Acidification drops more than 4% (Figure 36).

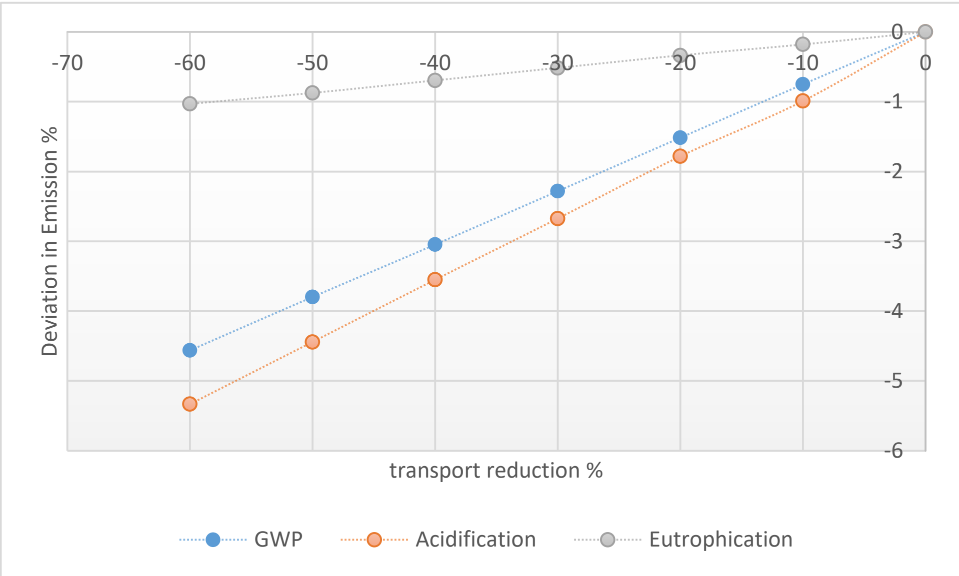

Figure 36 sensitivity analysis of transport in FPC

7.8 Mapping GWP of solar thermal system

The results of the f-chart method, regardless of demand, depend on some specific independent variables, the most determinative variable is the longitude of the site. The linear least-square of the calculated emission per kWh shows that the linear relation between GWP of the site, longitude of the site, elevation of the site, heating and cooling degree days (HDD & CDD) can explain 88% of the results (R^2=0.88). It is shown that with this linear relation, and input data of site location, we can estimate the GWP with excellent accuracy.

$$\mathbf{GWP = 0.000989865196746*Longitude - 2.52440109176e\text{-}06*HDD + 3.55788814647e\text{-}06*ELEVATION - 9.94896408677e\text{-}06*CDD - 0.00994146321478}$$

This equation is defined for FPC solar thermal system with 25m² collector area.

With implementing this equation, to data of 80 other cities all around Europe, the following map was formed.

Figure 37 contour map GWP using a solar thermal system with flat plate collector with collector area of 25m², for an apartment block, unit is gram CO_2 eq. per kWh

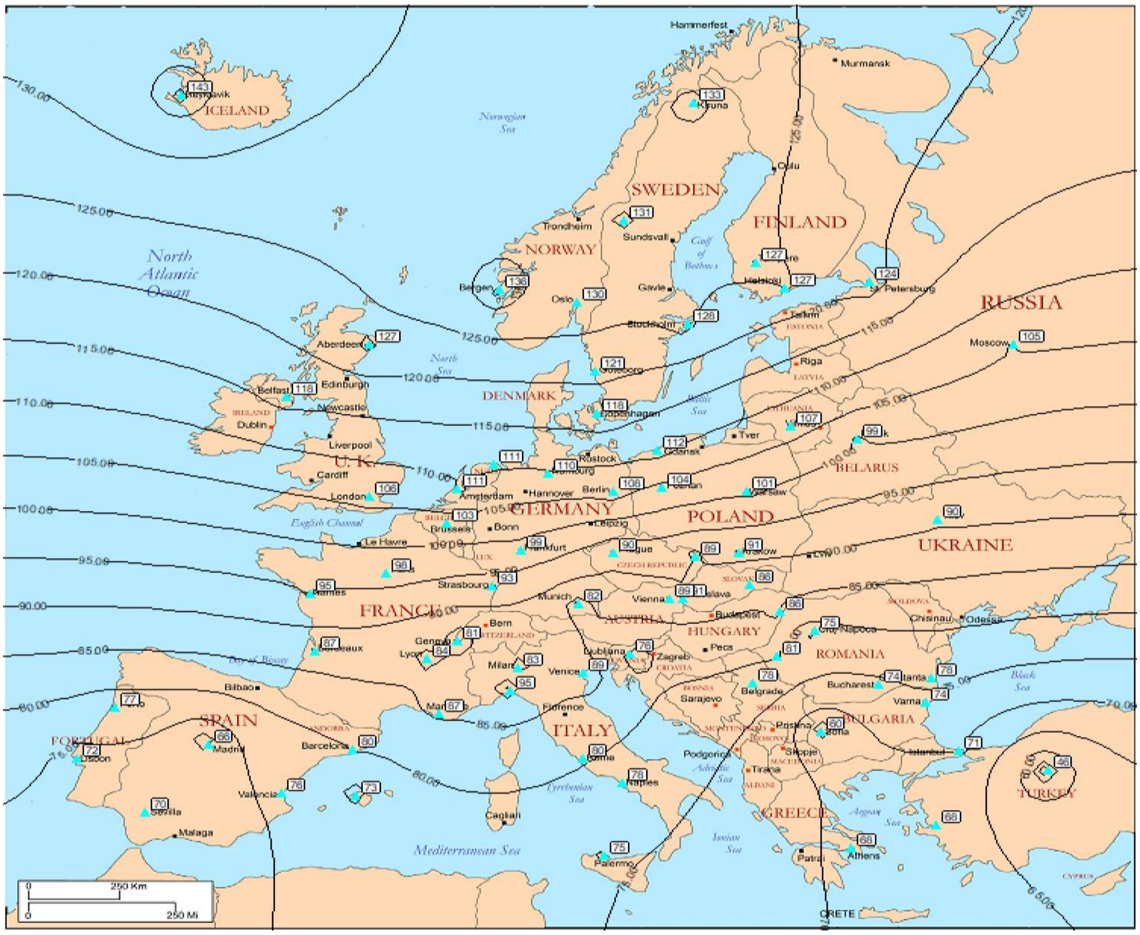

Figure 38 contour map GWP using a solar thermal system with flat plate collector with collector area of 25m², for a single-family house, unit is gram CO_2 eq. per kWh

8 Conclusion

The aim of this study was to calculate the environmental effect of using the solar thermal system, to generate heat for space heating and sanitary use hot water. The most important achievements of this study are listed below.

- To reach the maximum environmental performance of the solar thermal system, we need to avoid energy cut due to limited demand in warm seasons. One of the other ways to avoid energy cut is to use seasonal energy storage systems.
- In the Mediterranean region, the solar thermal system with 30m² collector area can cover up to 50% of heating demand of a single-family house.
- The performance and GWP of a solar thermal system is highly depends on the longitude of the installation site.
- The GWP of the solar thermal system with flat plate collector for a single-family house can be as low as 60 gr CO_2 eq. Per kWh for the Mediterranean region, up to more than 100 gr in Scandinavians.
- The GWP of the solar thermal system with Evacuated tube collector for a single-family house can be as low as 45 gr CO_2 eq. Per kWh for the Mediterranean region, and as high as more than 80 grams in Scandinavians.
- The minimum emission per thermal energy for a single family house is met in a collector area of 20-30 m².
- For an apartment block (or in general with end-user demand higher than the maximum production capacity of the system) the GWP can be as low as 20 gr CO_2 eq. Per kWh thermal energy.
- For apartment block, the emission will decrease with increasing the collector area.
- With comparing the environmental effect of using the solar thermal system, gas heater, oil heater, and pellet heater, for an apartment block, the solar thermal system is by far more environmentally friendly than other studied heating systems.
- In single-family house, in longitude northern than 50 degrees, pellet heater can be more environmental friendly than the solar thermal system.

9 Bibliography

[1] *Eurostat*. European Union Statistics Database (2018, March). Retrieved from Eurostat:http://ec.europa.eu/eurostat/statistics-explained/index.php/ Energy_consumption_in_households

[2] P.Zangheri, R. M. (2014). *Heating and cooling energy demand and loads for building types in different countries of the EU.* Milan: Intelligent Energy for Europe program of the European Union, https://www.entranze.eu/

[3] Rey-Martínez, F. J.-G.-G. (2007). *Life cycle analysis of a thermal solar installation*. Environmental Engineering Science,, 713-724. https://doi.org/10.1089/ees.2007.0115

[4] Hobbi, A. &. (2009). Experimental study on the effect of heat transfer enhancement devices in flat-plate solar collectors. *International Journal of Heat and Mass Transfer*, 4650-4658. https://doi.org/10.1016/j.ijheatmasstransfer.2009.03.018

[5] Martinopoulos, G. (2018). Life Cycle Assessment of Solar Energy Conversion Systems in Energetic Retrofitted Buildings. *Journal of Building Engineering. Volume 20, November 2018, Pages 256-263,* https://doi.org/10.1016/j.jobe.2018.07.027

[6] Ardente, F., Beccali, G., Cellura, M., & Lo Brano, V. (2005). Life cycle assessment of a solar thermal collector. *Renewable Energy*, *30*(7), 1031–1054. https://doi.org/10.1016/J.RENENE.2004.09.009

[7] Greening, B., & Azapagic, A. (2014). Domestic solar thermal water heating: A sustainable option for the UK? *Renewable Energy*, *63*, 23–36. https://doi.org/10.1016/J.RENENE.2013.07.048

[8] G.Martinopoulos. (2016). Energy efficiency and environmental impact of solar heating and cooling systems, . In T. G. R.Z. Wang, *Advances in solar heating and cooling* (pp. 43-59). Woodhead Publishing. https://doi.org/10.1016/B978-0-08-100301-5.00003-5

[9] Timo Hakkarainen, E. T. (2015). *The role and opportunities for solar energy in Finland and Europe.* VTT Technical Research Centre of Finland Ltd.

https://doi.org/10.13140/RG.2.1.2764.0486

[10] Watkins, E.David. (2011) Heating service in buildings: Design, Installation, commissioning and maintenance, Wiley, ISBN: 978-0-470-65603-7

[11] Solarbayer. *Calculating the correct buffer tank size*. Retrieved from solarbayer: https://www.solarbayer.com/Planning-aid-heat-storage.html

[12] Ksenya. (2011, August 7). *Types of Solar Thermal Collectors*. Retrieved from solartribune: https://solartribune.com/solar-thermal-collectors/

[13] Gautam, A., Chamoli, S., Kumar, A., & Singh, S. (2017). A review on technical improvements, economic feasibility and world scenario of solar water heating system. *Renewable and Sustainable Energy Reviews*, *68*, 541–562. https://doi.org/10.1016/J.RSER.2016.09.104

[14] Ardente,F. Beccali, G. Cellura, M , *Life cycle assessment of a solar thermal collector: sensitivity analysis, energy and environmental balances*, Renewable Energy 30, 2005, Volume 30, Issue 2, Pages 109-130 https://doi.org/10.1016/j.renene.2004.05.006

[15] Guinée, J., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A. d., . . . Huijbregts. (2002). *Handbook on life cycle assessment.* Dordrecht: Kluwer Academic Publishers. Retrieved from GABI: http://www.gabi-software.com/international/support/gabi/gabi-lcia-documentation/cml-2001/

[16] L.Brinson. (2012). *Is natural gas a good source of energy?* Retrieved from https://science.howstuffworks.com/environmental/energy/natural-gas-energy.html

[17] Mahalle, L. (2013). *comparative life cycle assemssment of Pellet, Natural gas, and heavy fuel oil, as heat energy resource.* Ottawa: FPinnovations. Prepared for Natural Resources Canada (CFS)

http://hardwoodinitiative.fpinnovations.ca/files/publications-reports/reports/comparative-lca-report.pdf

[18] Juhrich, K. (2016). *CO_2 Emission Factors for Fossil Fuels.* German Environment Agency (UBA).

https://www.umweltbundesamt.de/sites/default/files/medien/1968/publikationen/co2_emission_factors_for_fossil_fuels_correction.pdf

[19] Joshua Kneifel, P. L. (2015). *Building Industry Reporting and Design for Sustainability (BIRDS) New Residential Database Technical Manual* . NIST, National Institute of Standards and Technology US.

https://doi.org/10.6028/NIST.TN.1878

[20] Office of Energy Efficiency Canada. (2012). *Heating with Oil.* Ottawa: Natural Resources Canada's Office of Energy Efficiency.

https://www.nrcan.gc.ca/energy/products/categories/heating/furnaces/15774

[21] Stefano Caserini, J. G. (2011). *Life Cycle Assessment of pellets production and combustion chain in the European context.* Milan: Politecnico di Milano.

http://hdl.handle.net/10589/51561

[22] Duffie, J. A., Beckman, W. A., & Worek, W. M. (1994). Solar Engineering of Thermal Processes, 2nd ed. *Journal of Solar Energy Engineering*. https://doi.org/10.1115/1.2930068

[23] Kocer, A., & Atmaca, I. (2015). A COMPARISON OF FLAT PLATE AND EVACUATED TUBE SOLAR COLLECTORS WITH F-CHART METHOD. *Thermal Science and Technology,*Volume 35, P 77-86. ISSN 1300-3615

http://www.tibtd.org.tr/2015-1/77-86.pdf

[24] Klein, S. A., Beckman, W. A., & Duffie, J. A. (1976). A design procedure for solar heating systems. *Solar Energy*.

https://doi.org/10.1016/0038-092X(76)90044-X